



NEXT-

INTERNATIONAL CONFERENCE ON
NEXT - GENERATION DIGITAL TECHNOLOGIES | 2026

PROCEEDINGS

INTERNATIONAL CONFERENCE ON NEXT-GENERATION DIGITAL TECHNOLOGIES 2026

“Transforming The Digital Landscape with Emerging Technologies”

In Collaboration with:



PROCEEDINGS

**International Conference on Next
Generation Digital Technologies 2026
(NEXT-D 2026)**

PROCEEDINGS

International Conference on Next Generation Digital Technologies 2026 (NEXT-D 2026)

Medan, Indonesia, September 12-14, 2026

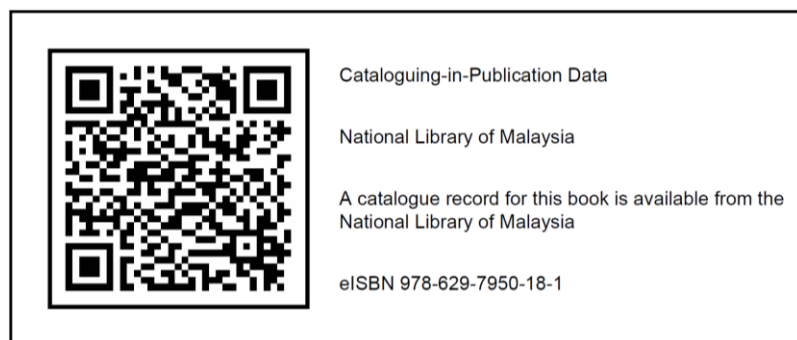
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Thank you.

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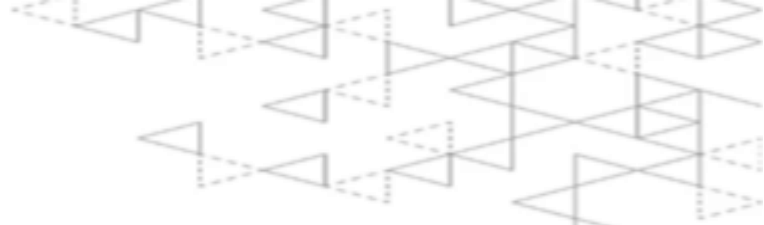
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ROYAL MESSAGE

ROYAL MESSAGE
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Proceedings of the International Conference on Next Generation Digital Technologies 2026
(NEXT-D 2026)



Assalamualaikum Warahmatullahi Wabarakatuh dan Salam Sejahtera

In the name of Allah, the Most Gracious, the Most Merciful. May peace and blessings be upon Prophet Muhammad SAW, his family, and his companions.

All praise is due to Allah, the Lord of the Worlds. It is by His grace, mercy, and blessings that I am given the opportunity to convey this Royal Message for the *Proceedings of the International Conference on Next-Generation Digital Technologies 2026 (NEXT-D 2026)*. This inaugural conference, organised by the Faizuddin Centre of Educational Excellence (FCoEE) in collaboration with Universiti Kebangsaan Malaysia (UKM), Universitas Muhammadiyah Sumatera Utara (UMSU), and Universiti Malaysia Kelantan (UMK), reflects a shared commitment to advancing research excellence, innovation, and international academic cooperation in the fields of digital technologies and artificial intelligence.

It has long been my aspiration to see stronger academic and research collaboration. I wish to extend my heartfelt congratulations and appreciation to the Faizuddin Centre of Educational Excellence (FCoEE), under the leadership of Professor Emeritus Datuk Dr. Kamarudin Hussin, for its vision and dedication in organizing this international conference and producing these proceedings. My sincere appreciation also goes to Professor Akrim, Rector of Universitas Muhammadiyah Sumatera Utara (UMSU), for graciously hosting this conference. I further commend Universiti Kebangsaan Malaysia (UKM) and Universiti Malaysia Kelantan (UMK) for their invaluable collaboration and commitment in ensuring the successful organisation of the conference and the rigorous review of the research manuscripts, thereby upholding the highest standards of scholarly publication.

I am encouraged that this conference provides a meaningful platform for researchers, academics, and professionals to exchange knowledge, strengthen partnerships, and foster innovations that address contemporary challenges. I am especially pleased that these collaborative efforts also support initiatives aimed at improving the quality of life of underserved communities, including the *Asnaf*, through education, research, and technological advancement.

In closing, I sincerely hope that these proceedings will serve as a valuable source of knowledge, inspire future research, and further strengthen the academic ties between Malaysia and Indonesia. May the outcomes of this conference contribute meaningfully to the advancement of education, scientific discovery, and innovation for the benefit of our societies and future generations.

May Allah Almighty bless these noble efforts and grant every success to all who have contributed to this important endeavour.

Wabillahaufik Walhidayah
Wassalamualaikum Warahmatullahi Wabarakatuh

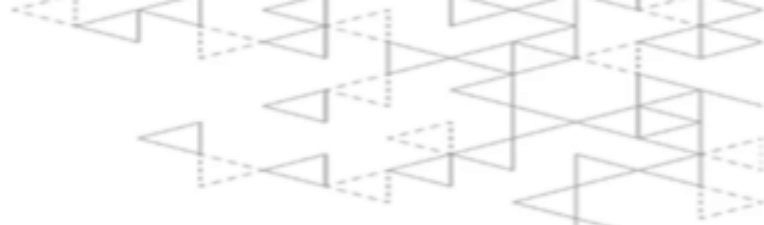
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MESSAGE FROM THE EXECUTIVE CHAIRMAN FAIZUDDIN CENTRE OF EDUCATIONAL EXCELLENCE (FCoEE)

Assalamualaikum Warahmatullahi Wabarakatuh and Greetings.

First and foremost, I would like to express my deepest gratitude to Allah the Almighty for granting me the opportunity to share my thoughts in the Proceedings Book of the International Conference on Next-Generation Digital Technologies 2026 (NEXT-D 2026). The theme of NEXT-D 2026, “Transforming the Digital Landscape with Emerging Technologies,” was selected in alignment with the mission of FCoEE, which is to transforming the Digital landscape with emerging technologies particularly in supporting *asnaf* education and enhancing the quality of life of the community.

I would like to extend my appreciation to **His Royal Highness The Crown Prince Of Perlis, Tuanku Syed Faizuddin Putra Ibni Tuanku Syed Sirajuddin Jamalullail** who has consistently demonstrated commitment and proactiveness in contributing ideas towards the advancement education.

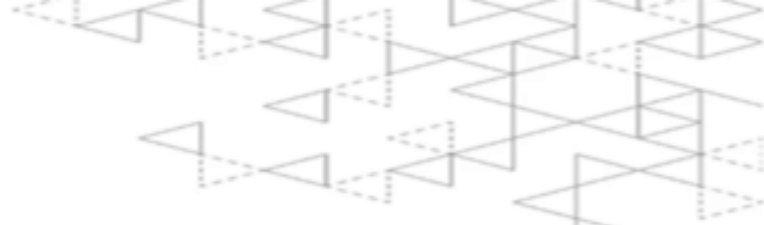
It is with great pleasure that I welcome all participants to the 1st International Conference on Next-Generation Digital Technologies (NEXT-D 2026). On behalf of the Organizing Committee, I extend my sincere appreciation to our co-organizers, collaborators, keynote speakers, reviewers, authors, sponsors, and participants for their invaluable contributions and commitment to making this inaugural conference a success. Your support has been instrumental in establishing NEXT-D 2026 as a platform for meaningful knowledge exchange and international collaboration.

I believe that these proceedings will serve as a valuable source of knowledge for the research community and encourage continued collaboration beyond this conference. I wish all participants a productive and rewarding conference experience and look forward to welcoming you to future editions of NEXT-D.

Finally, I would like to convey my highest appreciation and gratitude to the secretariat and researchers who have worked diligently in implementing the research grants, conducting the research activities, and fostering strong collaboration towards the successful publication of these conference proceedings.

Thank you.

PROFESOR EMERITUS DATUK DR. KAMARUDIN BIN HUSSIN, FASc
Executive Chairman
Faizuddin Centre of Educational Excellence (FCoEE)
Majlis Agama Islam dan Adat Istiadat Melayu Perlis (MAIPs)



PREFACE

It is our great pleasure to present the proceedings of the **1st International Conference on Next-Generation Digital Technologies (NEXT-D 2026)**, organized by the Faizuddin Centre of Educational Excellence (FCoEE) in collaboration with Universiti Kebangsaan Malaysia (UKM), Universitas Muhammadiyah Sumatera Utara (UMSU), and Universiti Malaysia Kelantan (UMK). As the inaugural edition of the conference, NEXT-D 2026 marks an important milestone in establishing an international platform for scholarly exchange and collaboration in the rapidly evolving fields of digital technologies and artificial intelligence (AI).

The theme of NEXT-D 2026, "Transforming the Digital Landscape with Emerging Technologies," reflects the conference's commitment to advancing innovative research and practical applications that shape the future digital ecosystem. The conference brings together postgraduate students, academics, researchers, industry professionals, and practitioners from Malaysia, Indonesia, and other countries to present their latest findings, exchange ideas, and foster interdisciplinary collaborations across digital technologies and AI.

NEXT-D 2026 features six (6) distinguished keynote speakers who share their expertise on emerging technologies and their transformative impact across academia, industry, and society. In addition, four (4) workshops provide participants with opportunities to enhance their technical knowledge and practical skills in cutting-edge AI and digital technologies. The conference also serves as a strategic platform for strengthening international academic partnerships, particularly between Malaysia and Indonesia, while supporting research initiatives that contribute to community development, including the empowerment of *asnaf* communities through technology-driven solutions.

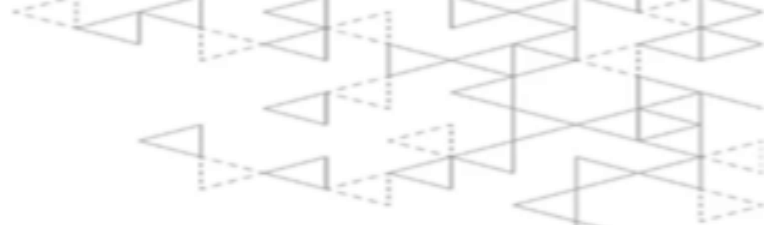
All submitted manuscripts underwent a rigorous single-blind peer-review process conducted by expert reviewers representing diverse areas of expertise from both local and international institutions. Each manuscript was carefully evaluated based on its originality, technical quality, significance, and relevance to the conference theme. A total of 29 manuscripts were accepted for presentation and publication in these proceedings. Selected high-quality papers will be invited for further enhancement and consideration for publication in reputable indexed journals, including journals indexed in Web of Science (WoS), Scopus, and MyCite.

Beyond disseminating high-quality research, NEXT-D 2026 aims to promote sustainable research collaboration among universities, industries, government agencies, and international partners. The conference is envisioned as a biennial event that continuously nurtures knowledge sharing, innovation, and strategic networking in digital technologies and AI. Through this initiative, the organizers aspire to strengthen research excellence, increase high-impact scholarly publications, and contribute meaningfully to advancing research performance within the region.

On behalf of the organizing committee, we extend our sincere appreciation to all authors for submitting their valuable research contributions, the Program Committee members and reviewers for their professionalism and dedication in maintaining the quality of the review process, the keynote speakers and workshop facilitators for sharing their expertise, and all sponsors, collaborators, and participants whose unwavering support has made the inaugural NEXT-D 2026 a success.

We hope that the papers presented in this volume will serve as valuable references for researchers, educators, practitioners, policymakers, and industry leaders, inspiring future innovations and collaborations that advance the digital landscape through emerging technologies and artificial intelligence. We look forward to welcoming the global research community to future editions of NEXT-D as we continue building a vibrant and impactful platform for knowledge exchange and scientific excellence.

**Rabiah Abdul Kadir
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INTRODUCTION

Welcome to the Proceedings of the **International Conference on Next-Generation Digital Technologies 2026 (NEXT-D 2026)**, a flagship academic gathering organized by the Faizuddin Centre of Educational Excellence (FCoEE) in collaboration with Universiti Kebangsaan Malaysia (UKM), Universitas Muhammadiyah Sumatera Utara (UMSU), and Universiti Malaysia Kelantan (UMK). This volume brings together a curated collection of original research contributions, review articles, and case studies that reflect the rapidly evolving landscape of digital technologies and the impact of artificial intelligence (AI) on society.

The theme of NEXT-D 2026 has been deliberately chosen in alignment with the mission of FCoEE to **transform the digital landscape through emerging technologies**, with a particular emphasis on supporting *asnaf* education and enhancing the overall quality of life of the wider community. In an era defined by artificial intelligence and its applications, robotics and the Internet of Things (IoT), digital entrepreneurship, AI in education, advanced computing, and the empowerment of *asnaf* communities through AI, the conference serves as a vital platform for scholars, practitioners, and industry leaders to share insights that bridge theoretical advancement with real-world societal benefit. The contributions featured herein explore how next-generation digital technologies can be harnessed inclusively, not only to advance scientific knowledge but also to create equitable opportunities for learning, empowerment, and sustainable human development.

The papers collected in these proceedings have undergone a rigorous double-blind peer review process, ensuring that each contribution meets the highest standards of academic quality, originality, and relevance. We extend our sincere appreciation to the members of the **Technical Programme Committee** and the dedicated reviewers, whose tireless efforts have shaped this volume. Our gratitude also goes to the keynote speakers who have generously shared their expertise, and to the authors from across the globe, whose innovative work forms the heart of this conference.

It is our sincere belief that these proceedings will serve as a **valuable source of knowledge for the research community**, offering fresh perspectives, rigorous methodologies, and inspiring directions for future inquiry. Beyond the dissemination of research, we hope that NEXT-D 2026 will encourage **continued collaboration** among academia, industry, and policymakers, fostering partnerships that extend well beyond the boundaries of this conference. The dialogue initiated here, we trust that the dialogue initiated here will catalyze new research initiatives, collaborative projects, and educational programmes that translate digital innovation into tangible benefits for the community.

We wish all participants a **productive and rewarding conference experience**, filled with meaningful exchanges, new connections, and renewed inspiration. May the ideas discussed at NEXT-D 2026 contribute to a more intelligent, inclusive, and human-centred digital future that extends well beyond these pages.

Organizing Committee NEXT-D 2026

ARTIFICIAL INTELLIGENCE & ITS APPLICATION

Enhancing Teaching and Learning in Mathematics: The Development of a Virtual Reality-Based TelEdu-MathG

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ABSTRACT — The rapid advancement of digital technology has significantly influenced mathematics education, particularly through the emergence of immersive learning environments. This study aims to develop and evaluate the TelEdu-VR MathG learning model, a virtual reality (VR)-based application integrated with gamification to enhance elementary school students' understanding of geometry concepts. The study employed a Research and Development (R&D) methodology based on the Borg and Gall model, consisting of ten systematic development stages, and incorporated Van Hiele's theory of geometric thinking as the pedagogical foundation. The system was developed using VR technology (Meta Quest 3) to create an interactive three-dimensional learning environment. The product was tested in SD Negeri 13 Banda Aceh, involving 28 students, three mathematics teachers, and the school principal. The findings indicate that TelEdu-VR MathG is highly feasible and effective as a learning medium. Expert validation yielded a score of 89%, confirming a high level of validity and appropriateness for educational use. Furthermore, the N-Gain analysis result exceeded 0.70, indicating a high improvement in students' learning outcomes. Observational data also revealed positive changes in students' learning behavior, characterized by increased interaction and engagement both inside and outside the classroom through repeated exposure to the VR environment. Overall, TelEdu-VR MathG demonstrates strong potential as an innovative VR-based instructional tool that supports immersive, interactive, and game-based mathematics learning. The integration of VR technology in geometry instruction significantly enhances students' motivation, engagement, and academic performance. This study suggests that the TelEdu-VR MathG model offers promising opportunities for advancing digital transformation in mathematics education and improving the quality of learning experiences in elementary schools.

KEYWORDS: Educational Technology, Gamification, Mathematics Education, TelEdu-VR MathG, Virtual Reality (VR).

I. INTRODUCTION

The rapid advancement of digital technology has significantly influenced contemporary educational practices. Digital technologies provide innovative approaches to addressing global educational challenges, particularly those related to improving educational quality. These technological developments have led to the creation of diverse learning

media that support teaching and learning processes in schools. In mathematics education, the integration of engaging and interactive learning media can enhance students' interest, motivation, and learning experiences, making mathematical concepts more accessible and enjoyable to learn [1], [2]. Nevertheless, one of the major challenges in contemporary education is transforming abstract mathematical concepts into concrete, intuitive, and accurate mental representations for students. Due to their abstract nature, mathematical concepts are often difficult for students to comprehend and are frequently regarded as one of the most challenging areas of learning [1]. Although solid geometry concepts are commonly introduced through concrete representations in traditional classroom instruction, students often continue to face challenges in achieving a deep understanding of these concepts [3]. Therefore, the integration of 3D virtual visualization is essential to enhance students' conceptual understanding. By offering immersive and interactive learning experiences, 3D virtual environments enable students to engage directly with scientific and mathematical concepts, thereby improving comprehension and learning outcomes [4], [5].

TelEdu-VR MathG serves as an innovative educational technology that enhances students' creativity by facilitating the visualization of abstract mathematical concepts and phenomena beyond the constraints of the physical world. Through its interactive, immersive, and imaginative learning experiences, TelEdu-VR MathG promotes creativity while establishing a futuristic virtual reality (VR)-based learning environment. Such technology-enhanced learning transitions play a crucial role in improving knowledge construction, academic achievement, student engagement, collaborative learning, and the overall quality of students' educational experiences [6]. The implementation of Virtual Reality (VR) headsets in mathematics classrooms functions as an innovative digital learning tool that facilitates conceptual understanding, mathematical reasoning, visualization, and problem-solving competencies [7], [8], [9], [10], [11]. Virtual Reality (VR) technology is widely recognized as an innovative educational approach because it enables the creation of immersive virtual learning environments tailored to learners' specific needs [12].

II. LITERATURE REVIEW

A. *Virtual Reality and Gamification for Immersive Mathematics Learning (Heading 2)*

Virtual Reality (VR) technology has significantly transformed a wide range of disciplines, particularly psychology and education [13], [14], [15]. The use of Virtual Reality (VR) environments facilitates interactive learning experiences for students, especially in mathematics education, where abstract concepts such as geometry can be explored more effectively [16], [17], [18], [19], [20], [21], [22]. Gamification is among the most commonly employed approaches for implementing Virtual Reality (VR) in educational environments, enhancing learner engagement and motivation throughout the learning process [23], [24]. Gamification-based learning has emerged as an effective pedagogical approach for improving students' mathematical proficiency. Integrating digital game elements into the learning process, this approach promotes engaging and enjoyable mathematics learning experiences, thereby supporting the development of students' digital mathematical literacy and competencies [25], [25], [26], [27].

The integration of games and virtual learning environments in education has been widely recognized as an effective approach for enhancing students' attention, motivation, knowledge retention, and academic performance [28], [29], [30], [31]. Findings from 52% of the studies reviewed across Europe, North America, and Asia indicate that the use of Virtual Reality (VR) significantly contributes to the creation of immersive learning experiences [32]. Participation in immersive learning environments has been associated with enhanced critical thinking skills, with students outperforming those exposed to conventional teaching methods [33], [34]. Therefore, the implementation of MathG gamification in conjunction with Virtual Reality (VR) headsets has the potential to enhance student engagement by creating a positive and immersive learning environment.

B. *The Potential of TelEdu-VR MathG in Enhancing Mathematics Learning*

The adoption of immersive technologies in mathematics education has been shown to significantly enhance students' learning behaviors, particularly in understanding abstract mathematical concepts [35], [36], [37]. The integration of digital technology enhances students' understanding of real-world problems by providing opportunities to interact with and explore simulated virtual environments in an immersive learning context [19], [38]. The development of the TelEdu-VR MathG application enables teachers to establish a more conducive, immersive, and engaging learning environment. For learners, the application offers opportunities to explore abstract mathematical concepts, evaluate conceptual understanding, and achieve self-directed learning through game-based activities. The integration of virtualization technology within TelEdu-VR MathG constitutes a novel contribution to mathematics education by combining immersive 3D visualization, interactive exploration, and gamified learning experiences within a single educational platform. This approach not only enhances students' creativity and spatial reasoning but also supports the resolution of complex mathematical problems. Consistent with constructivist learning theory, virtualization technology provides an open-ended and creative learning space that extends beyond the constraints of traditional classroom

instruction, thereby promoting imagination, critical thinking, and creative problem-solving abilities [39]. Therefore, to ensure the effective integration of Virtual Simulation (VS) technology, careful consideration must be given to the design of appropriate systems, the implementation of realistic instructional activities, and the collection and analysis of accurate data.

Technological advancements have transformed educational practices across diverse fields of study, with mathematics representing a discipline particularly well-suited for the integration of digital technologies into teaching and learning. Empirical evidence suggests that technology-enhanced interventions in mathematics education provide substantial benefits, including improved academic performance, increased student engagement, and the promotion of higher-order thinking skills. Moreover, the integration of technology into elementary mathematics instruction has been demonstrated to significantly enhance students' mathematical achievement and learning experiences [40]. Interactive software, simulations, and dynamic graphical representations have demonstrated significant potential in improving students' comprehension of complex mathematical concepts. Such technologies support the visualization of abstract mathematical ideas, facilitate the exploration of conceptual relationships, and foster active participation in the learning process. Moreover, the rapid evolution of digital technology has resulted in the widespread integration of teachers, students, and parents into diverse digital environments through the use of both hardware and software technologies. This growing digital engagement has transformed educational practices and created new opportunities for technology-enhanced learning [41]. Although many of these technologies were initially designed for non-educational applications, innovations such as holographic technology and Virtual Reality (VR) headsets have increasingly been adapted for educational use. Nevertheless, successful technology integration in education involves more than simply incorporating digital tools into the classroom. It necessitates thoughtful pedagogical planning, professional development for educators, and a clear alignment between technological applications and established learning objectives.

III. METHODS AND MATERIAL

A. *Research Methods*

This study employed a Research and Development (R&D) methodology consisting of ten stages of research and development as proposed by Borg and Gall [1]. These stages include: (1) Research and Information Gathering, (2) Optimization Design Planning, (3) Initial Product Development, (4) Preliminary Field Testing, (5) Initial Product Revision, (6) Expert Validation, (7) Large-Scale Field Testing, (8) Data Analysis, (9) Final Product Revision, and (10) Dissemination and Reporting of the Final Research Product [42]. The structure of MathG is based on Van Hiele's Theory of Geometric Thinking, particularly Level 0 (Visualization), Level 2 (Informal Deduction), Level 3 (Deduction), and Level 4 (Rigor). These levels are integrated into the application to support the gradual progression of students' geometric thinking from visual recognition to formal reasoning and rigorous mathematical understanding [43]. In this study, the first-stage field trial of the TelEdu-

VR MathG application was conducted with students and teachers at SDN 13 Banda Aceh. The preliminary product testing involved 28 students, three mathematics teachers, and the school principal. The trial was undertaken to assess the feasibility and implementation of the application in supporting mathematics learning at the elementary school level.

B. Virtual Reality Hardware and Software Configuration

Virtual Reality (VR) is a technology that simulates environments resembling the real world. In education, VR has been widely recognized as a transformative tool capable of providing multisensory learning experiences that enhance student motivation and support deeper conceptual understanding. The application of VR technology enables the creation of immersive simulation environments that students can explore within a 360-degree virtual space. Consequently, VR-based immersive learning allows students to experience abstract mathematical concepts within realistic three-dimensional (3D) environments. VR offers an immersive and interactive learning environment that engages students more deeply with instructional content, thereby improving knowledge retention and facilitating the understanding of complex concepts. Furthermore, VR enables learners to visualize and explore educational content in ways that are difficult to achieve through traditional teaching methods. Virtual reality systems utilize various input devices, including VR controllers, which allow users to manipulate virtual hands, grasp objects, and interact with elements within the virtual environment. In addition, joysticks can serve as alternative navigation controls, particularly in applications such as MathG. In this study, the researchers employed the Meta Quest 3 VR system, equipped with a 128 GB Meta Quest 3S Head-Mounted Display (HMD), as illustrated in Figure 1:



Figure 1. Oculus Meta Quest 3 Virtual Reality VR.

C. VR Learning Platform and System Architecture

Virtual Reality (VR) technology was employed as the primary instructional medium in this study. VR is a digital innovation characterized by immersive, interactive, and three-dimensional virtual environments that enable users to engage with simulated experiences in a realistic manner. The utilization of VR in education provides opportunities to create dynamic learning environments that facilitate experiential learning through exploration, observation, and hands-on interaction. Considering that students possess diverse learning styles, including visual, verbal, kinesthetic, and reading/writing preferences, VR was selected due to its capacity to accommodate multiple modes of information acquisition and processing. Furthermore, VR supports various forms of learner engagement, including active, passive, and experiential participation, thereby promoting

meaningful knowledge construction. Through immersive learning experiences, students can interact directly with virtual objects and phenomena, enabling them to develop conceptual understanding in ways that may not be achievable through conventional instructional media [44].

Consequently, the integration of information technology into educational settings is imperative, particularly amid the ongoing paradigm shift in teaching and learning. Through the use of Virtual Reality (VR), learners engage in a multi-user, three-dimensional (3D), and immersive virtual environment that facilitates interactive learning experiences. Within this environment, users are tasked with controlling a virtual charged object and navigating predefined pathways while avoiding contact with boundary constraints. Repeated collisions with the boundaries trigger an automatic reset mechanism that returns the user to the initial starting position. The application was developed using Java for algorithm implementation and XML for user interface design. The overall application design and interface are presented in Figure 2.

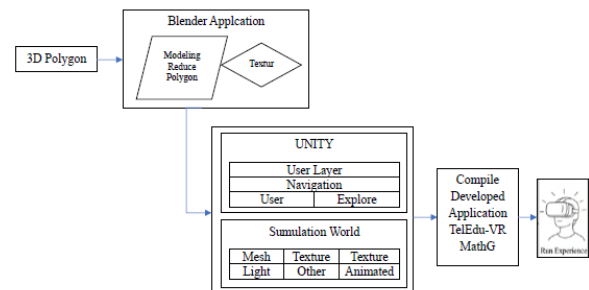


Figure 2. VR System Design Process.

D. Virtual Reality Application and Learning Environment

The TelEdu-VR MathG application provides effective learning content and a systematically organized instructional support framework. Virtual Reality (VR) holds considerable potential to foster personalized and inclusive learning experiences, especially in Science, Technology, Engineering, and Mathematics (STEM) education, in line with the United Nations Sustainable Development Goals (SDGs) under the 2030 Agenda for Sustainable Development [45]. TelEdu-VR MathG is an immersive mathematics learning application that enables students to engage with mathematical concepts through a Virtual Reality (VR) environment. By wearing a VR headset, students enter a three-dimensional (3D) virtual classroom where they can interact with and manipulate various geometric objects, including cubes, rectangular prisms, cylinders, pyramids, and other three-dimensional shapes. The system provides real-time feedback and performance scores while simultaneously tracking students' learning engagement. Designed for elementary school learners, TelEdu-VR MathG integrates VR technology with geometry instruction to enhance conceptual understanding and learning experiences. Geometry has emerged as one of the most widely investigated mathematical topics in AR/VR-based learning due to its inherently visual and spatial nature, which aligns well with immersive learning environments [46], [47], [48]. The review findings indicated that only a limited number of articles ($n = 11$) among the 100 studies examined addressed the implementation of Virtual Reality (VR) by

elementary school teachers [49]. Studies on educational systems utilizing Virtual Reality (VR) have reported several significant findings. Constructivism is the most widely applied learning theory in VR-based education, whereas experiential learning is regarded as the most appropriate instructional approach for immersive learning environments. In addition, learning gamification has been recognized as the most promising direction for future research and educational innovation [50].

IV. RESULTS AND DISCUSSION

At the initial stage of the study, a literature review and field investigation were conducted at SD Negeri 13 Banda Aceh. The results of the field investigation indicated that identifying mathematics learning loss among students necessitates a comprehensive review of mathematical concepts and topics that are frequently challenging for students to comprehend. To date, the optimized TelEdu-VR MathG has successfully completed the laboratory validation phase of the VR prototype at the UUI Computer Laboratory. The effectiveness evaluation showed a pretest–posttest N-Gain score exceeding 0.70 among students at SD Negeri 13 Banda Aceh, while expert validation achieved a score of 89%, confirming the high validity and feasibility of the developed learning media. The visual design of the TelEdu-VR MathG model intended for implementation is illustrated in Figure 3.



Figure 3. View of the TelEdu-VR MathG Model.

TelEdu VR is a learning environment designed for geometry education, specifically three-dimensional shapes, based on Virtual Reality (VR) technology in mathematics instruction. It enables fifth-grade elementary school students to virtually observe and explore basic geometric concepts, select objects, and interact with various components of solid shapes as if they were physically present in the learning space. To evaluate students' learning behavior, a validated learning behavior instrument was employed. The instrument consisted of three sections: 27 items assessing classroom learning behavior, 25 items measuring learning motivation, and 15 items examining out-of-class learning behavior [51]. This validation process was conducted as a content validation of the developed E-Module on Geometry. The content validation was carried out by three elementary school teachers from SD 13 Banda Aceh City who teach mathematics and have at least five years of teaching experience in the subject. Furthermore, media validation was conducted by media and game design experts to ensure that the design of the developed TelEdu-VS MathG application is valid. Technical validation was also performed by a programmer or IT specialist, in this case a lecturer in Information Technology at Universitas Ubudiyah Indonesia

who has been teaching programming courses for approximately the past five years.

The TelEdu-MathG system was developed and implemented using a Virtual Reality (VR) environment to support interactive mathematics learning. The system is designed to simulate geometry and algebra concepts within an immersive 3D space, enabling students to manipulate objects, visualize abstract mathematical structures, and engage in experiential learning. The implementation was conducted over a one-semester learning cycle using a classroom learning behavior questionnaire, student motivation, and students' social interaction outside the classroom. These parameters were simulated using MATLAB by assigning quantitative values to each variable. Schematically, the form of the nonlinear differential equation is expressed as follows:

$$\frac{dS_2}{dt} = \alpha_2 S_2 + \varphi_2 R_2 - \beta_3 S_2 I_2 - \beta_4 S_2 I_1 - \mu S_2 \quad (1)$$

$$\frac{dE_2}{dt} = \beta_3 S_2 I_2 + \beta_4 S_2 I_1 - \delta_2 E_2 - \mu E_2 \quad (2)$$

$$\frac{dI_2}{dt} = \delta_2 E_2 + \gamma_2 S_2 I_2 - \sigma_2 I_2 - \mu I_2 \quad (3)$$

$$\frac{dR_2}{dt} = \sigma_2 I_2 - \varphi_2 R_2 - \mu R_2 \quad (4)$$

Let $N = S_1 + S_2 + E + I_1 + I_2 + R$, then $\frac{dN}{dt} = 0$, hence $N(t) = k$, where k is a positive constant, since $N(t)$ constant.

Based on the variables, initial values, and parameters used in the simulation model of Equations (1) to (4), the implementation was carried out using MATLAB 2010b. The corresponding program is shown in Figure 4.

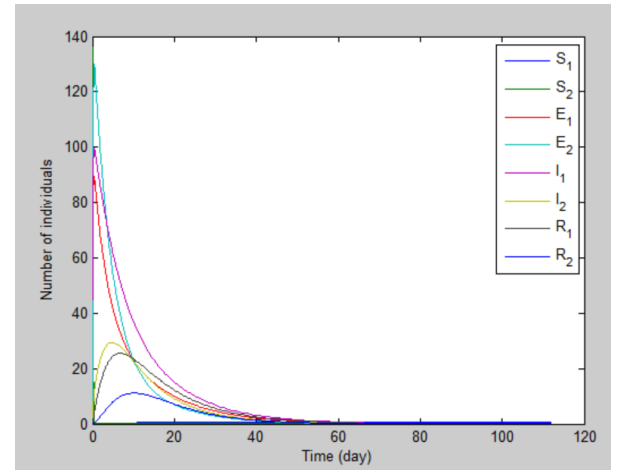


Figure 4. The Process of Changing Learning Behavior in One Semester

Through Figure 4, it can be observed that changes in students' learning behavior begin on day 60, which corresponds to the first day of monitoring the learning behavior simulation, and reach a value of zero on day 120. This indicates that by day 120, no students should experience learning difficulties if the TelEdu-VR MathG learning system is properly implemented in the classroom. During the VR-assisted learning phase, students are introduced to dynamic mathematical representations such as 3D geometric shapes, coordinate transformations, and

problem-solving scenarios. Interaction data were collected from several learning indicators, including task completion time, problem-solving accuracy, level of engagement (interaction frequency), and cognitive response behavior. These indicators were analyzed to examine changes in learning performance over time.

Based on Figure 4, it can be observed that as the VR-based learning session progresses, student engagement increases significantly, as indicated by a higher frequency of interactions with virtual objects and learning modules. At the same time, the error rate in completing mathematics tasks gradually decreases, while the conceptual understanding score shows a steady improvement. In the initial stage, students still require substantial guidance to understand spatial representations. However, after repeated interactions within the VR environment, they demonstrate enhanced spatial reasoning abilities and improved problem-solving efficiency.

Furthermore, the immersive characteristics of VR contribute to reducing learning anxiety while enhancing conceptual clarity, particularly in geometry and spatial visualization topics. The integration of visual, auditory, and interactive feedback strengthens the cognitive linkage between abstract mathematical concepts and their real-world representations. Based on the observed learning behavior, the mathematics learning process within the TelEdu-MathG environment can be categorized into three stages: the initial adaptation stage (characterized by low interaction and a high error rate), the exploration stage (characterized by increasing interaction and moderate improvement), and the mastery stage (characterized by stable high interaction and a low error rate). Overall, the research findings indicate that the VR-based TelEdu-MathG learning system significantly enhances student engagement and improves mathematics learning outcomes through an immersive, interactive, and concept-rich learning environment.

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REFERENCES

- Mutiawati, "Development of Mathematics Learning for PGSD Students Using Video Game with Comic Storyline," vol. 6, no. 2, pp. 203–209, 2020, doi: <https://doi.org/10.3314/jes.v6i2.1161>.
- G. Bischof *et al.*, "Bringing differential equations to life by two- and three-dimensional visualizations of numerically simulated dynamic systems," 2022. doi: [10.18260/1-2--40535](https://doi.org/10.18260/1-2--40535).
- Q. Liu, L. Sun, J. Ma, S. Yu, and L. Wu, "Geometry Wall: An Embodied Gesture-based Game for Supporting Spatial Ability," 2022. doi: [10.1109/TALE54877.2022.00050](https://doi.org/10.1109/TALE54877.2022.00050).
- L. Yurisma, V. S. Dewi, and Mutiawati, "Pembuatan Animasi 3D Taman Shulthanah Shafiatuddin Menggunakan Blender," *J. Tek. Inform.*, vol. 9, no. 1, pp. 120–136, 2021.
- H. A. Poonja, M. A. Shirazi, M. J. Khan, and K. Javed, "Engagement detection and enhancement for STEM education through computer vision, augmented reality, and haptics," *Image Vis. Comput.*, vol. 136, 2023, doi: [10.1016/j.imavis.2023.104720](https://doi.org/10.1016/j.imavis.2023.104720).
- M. Mutiawati *et al.*, "Using the Flipped Classroom Model to Prevent Sexual Violence in Special Needs Children," *J. Educ. Manag. Learn.*, vol. 1, no. 2, pp. 55–63, Nov. 2023, doi: [10.60084/jeml.v1i2.107](https://doi.org/10.60084/jeml.v1i2.107).
- N. Afifah, A. K. Putra, and A. Hibatul Haqqi, "Virtual Reality Integration in Geography: Meningkatkan Environmental Problem Solving Ability Siswa pada Kajian Konservasi DAS," *J. Educ. Action Res.*, vol. 8, no. 1, pp. 11–22, Apr. 2024, doi: [10.23887/jear.v8i1.67943](https://doi.org/10.23887/jear.v8i1.67943).
- N. H. A. Ismail, S. A. B. Awwad, R. Thinakaran, W. B. Quah, and M. Muniandy, "Virtual Reality and Gamification in Hospitality Education at Front Desk," *TEM J.*, vol. 13, no. 3, pp. 1973–1980, 2024, doi: [10.18421/TEM133-25](https://doi.org/10.18421/TEM133-25).
- T. Weng, C. K. Li, Y. Kawasaki, and I. C. Chao, "Virtual Game on Everyday Statistics," 2024. doi: [10.1007/978-3-031-65884-6_6](https://doi.org/10.1007/978-3-031-65884-6_6).
- Mutiawati, "Penerapan Model Pembelajaran Kooperatif Tipe Group Investigation dalam Menganaliskemampuan Pemecahan Masalah Matematis dan Self-Concept Mahasiswa," *J. Educ. Sci.*, pp. 70–76, 2019, [Online]. Available: <http://jurnal.uui.ac.id/index.php/jes/article/view/361>
- M. S. Y. Jong, X. Zhai, and W. Chen, "Innovative Uses of Technologies in Science, Mathematics and STEM Education in K-12 Contexts," 2024. doi: [10.1007/s10763-024-10530-x](https://doi.org/10.1007/s10763-024-10530-x).
- S. Yadav, "Empowering educators with augmented and virtual reality: Integrating AR and VR for enhanced interactive learning environment," 2024. doi: [10.4018/979-8-3693-1310-7.ch005](https://doi.org/10.4018/979-8-3693-1310-7.ch005).
- M. Kuleva, "Exploring the Integration of Virtual Reality in Physical Education: A Comprehensive Review," 2024. doi: [10.17770/etr2024vol2.8057](https://doi.org/10.17770/etr2024vol2.8057).
- H. Guillen-Sanz, G. L. Pérez, and I. Q. Bayona, "Design and Development of an Immersive Virtual Reality Serious Game With Biofeedback for Physiological Regulation: Alice, Beyond Reality," 2024. doi: [10.34190/ecgbl.18.1.2821](https://doi.org/10.34190/ecgbl.18.1.2821).
- Z. Papamitsiou, S. A. Petersen, C. Psyllaki, G. Lamvik, and H. Torvatn, "On the Design of Gamified Learning Analytics for Immersive Virtual Reality Games," 2025. doi: [10.1007/978-3-031-78269-5_11](https://doi.org/10.1007/978-3-031-78269-5_11).
- M. D. Setyawan, L. El Hakim, and T. A. Aziz, "Kajian Peran Virtual Reality (VR) Untuk Membangun Kemampuan Dialogis Siswa Dalam Pembelajaran Matematika," *J. Pendidik. Indones.*, vol. 4, no. 02, pp. 122–131, Feb. 2023, doi: [10.36418/japendi.v4i02.1592](https://doi.org/10.36418/japendi.v4i02.1592).
- L. Gerini, M. Chessa, G. Delzanno, G. Guerrini, and F. Solari, "A 3D Visual Programming Language for Tangible Coding in Extended Reality," 2024. doi: [10.1007/978-3-031-67351-1_46](https://doi.org/10.1007/978-3-031-67351-1_46).
- M. U. Tariq, "Gamification and virtual reality: Transforming early childhood language learning," 2025. doi: [10.4018/979-8-3693-7437-5.ch002](https://doi.org/10.4018/979-8-3693-7437-5.ch002).
- A. Ruiz de la Torre Acha, R. M. Rio Belver, J. Fernandez Aguirrebeña, and C. Merlo, "Application of simulation and virtual reality to production learning," *Educ. Train.*, vol. 66, no. 2–3, pp. 145–165, 2024, doi: [10.1108/ET-02-2023-0051](https://doi.org/10.1108/ET-02-2023-0051).
- L. A. Thomsen, N. C. Nilsson, R. Nordahl, K. B. Støvelbaek, and C. B. Mundbjerg-Sunne, "An Immersive Geometry Environment for Mathematics Education: Taxonomy and Preliminary Evaluation," 2023. doi: [10.1109/VRW58643.2023.00112](https://doi.org/10.1109/VRW58643.2023.00112).
- J. Trgalová and M. Tabach, "Introduction to How Digital Resources Transform Content," 2024. doi: [10.1007/978-3-031-45667-1_11](https://doi.org/10.1007/978-3-031-45667-1_11).
- M. Cotič, D. Doz, M. Jenko, and A. Žakelj, "Mathematics education: What was it, what is it, and what will it be?," 2024. doi: [10.29333/iejme/14663](https://doi.org/10.29333/iejme/14663).
- I. N. Ismail *et al.*, "A Review of Virtual Reality Application on STEM Based Education," 2024. doi: [10.1063/5.0185720](https://doi.org/10.1063/5.0185720).
- K. Nagel and M. Rauschenberger, "The use of gamification and virtual reality in higher education: A literature review," 2024.
- F. Yahya *et al.*, "Digital game-based learning of mathematics (DigiMaps) for pre-school," in *AIP Conference Proceedings*, 2024, p. 040043. doi: [10.1063/5.0148839](https://doi.org/10.1063/5.0148839).

- [26] A. Christopoulos, S. Mystakidis, J. Kurczaba, M. J. Laakso, and C. Stylios, "Is Immersion in 3D Virtual Games Associated with Mathematical Ability Improvement in Game-Based Learning?," *Int. J. Sci. Math. Educ.*, vol. 22, no. 7, pp. 1479–1499, 2024, doi: 10.1007/s10763-023-10440-4.
- [27] S. Mystakidis and A. Christopoulos, "Teacher Perceptions on Virtual Reality Escape Rooms for STEM Education," *Inf.*, vol. 13, no. 3, 2022, doi: 10.3390/info13030136.
- [28] J. D. Azofeifa, V. Rueda-Castro, L. J. Gonzalez-Gomez, G. M. Chans, P. Caratozzolo, and J. Noguez, "Engaging Engineering Education Through Multi-Sensory Virtual Decision-Making Centers: A Gamified Approach," 2024. doi: 10.1109/EDUCON60312.2024.10578682.
- [29] E. Bubar, S. Agolini, D. Jaber, and A. Wright, "Three Methods for Adapting Physical Games to Virtual Formats in STEM Courses – Easy (Google Suite), Medium (Web GL Games in Unity) and Hard (Virtual Reality)," 2021. doi: 10.1007/978-3-030-78645-8_18.
- [30] M. Lapina, E. A. Mary Anita, A. Bagautdinova, and M. Pukhova, "Gamification and Game-Based Learning: A Systematic Review and Comparative Analysis," 2025. doi: 10.1007/978-3-031-78776-8_53.
- [31] A. Sypsas, E. Paxinou, V. Zafeiropoulos, and D. Kalles, "Virtual Laboratories in STEM Education: A Focus on Onlabs, a 3D Virtual Reality Biology Laboratory," 2024. doi: 10.1007/978-3-031-70771-1_16.
- [32] Q. Wu, Y. Wang, L. Lu, Y. Chen, H. Long, and J. Wang, "Virtual Simulation in Undergraduate Medical Education: A Scoping Review of Recent Practice," 2022. doi: 10.3389/fmed.2022.855403.
- [33] M. Firdaus, Mukhtar, M. B. Darari, and Z. Azis, "The Effect of Immersive Virtual Reality-Based Learning Activities on Students Critical Thinking Skills," 2022. doi: 10.1063/5.0113535.
- [34] M. Holly, S. Brettschuh, and J. Pirker, "An Immersive Laboratory Environment for a Customized Learning Experience," 2024. doi: 10.1007/978-3-031-47328-9_27.
- [35] M. Cabanag, "MathVR: Teaching Vector Arithmetic Using Virtual Reality," 2023. doi: 10.1145/3610540.3627012.
- [36] P. M. L. Ng, J. K. Y. Chan, T. M. Wut, M. M. Lau, and M. Kan, "The Effects of Gamification and VR in Encouraging Pro-Environmental Behavior," 2024. doi: 10.1109/ICIET60671.2024.10542747.
- [37] J. Tito Cruz, V. R. Coluci, and R. Moraes, "ORUN-VR2: a VR serious game on the projectile kinematics: design, evaluation, and learning outcomes," *Virtual Real.*, vol. 27, no. 3, pp. 2583–2604, 2023, doi: 10.1007/s10055-023-00824-w.
- [38] I. Mierluş-Mazilu and F. Yilmaz, "Teaching Mathematics in STEM Education," 2024. doi: 10.1007/978-3-031-49218-1_11.
- [39] Z. H. Zhao, "Application Research of Virtual Reality Technology in Enhancing Artistic Creativity of Preschool Children," 2025. doi: 10.1007/978-981-96-0096-0_7.
- [40] M. K. Burns, M. D. Duesenberg-Marshall, M. E. Romero, K. J. Sussman-Dawson, and E. Singell, "Meta-Analysis of the Effect of Technology-Based Mathematical Fact Practice on Mathematics Outcomes," *J. Spec. Educ. Technol.*, vol. 40, no. 3, pp. 332–343, Sep. 2024, doi: 10.1177/01626434241288199.
- [41] X. Li and R. Zaki, "Harnessing the Power of Digital Resources in Mathematics Education: The Potential of Augmented Reality and Artificial Intelligence," 2024. doi: 10.1007/978-3-031-50139-5_10.
- [42] M. D. Borg W.R & Gall, *Educational Research: An Introduction*. Boston: Pearson Education inc, 2002.
- [43] F. S. Hilyana, "Workshop Pembuatan Aplikasi Information And Communication Technology (ICT) Dalam Pembelajaran Bagi Guru Ipa Lembaga Pendidikan Ma'arif Kudus," *ABDIMAS UNWAHAS*, vol. 5, no. 1, Apr. 2020, doi: 10.31942/abd.v5i1.3337.
- [44] O. T. Laseinde and D. Dada, "Enhancing teaching and learning in STEM Labs: The development of an android-based virtual reality platform," *Mater. Today Proc.*, vol. 105, no. C, pp. 240–246, 2022, doi: 10.1016/j.matpr.2023.09.020.
- [45] B. Aruanno, F. Tamburrino, P. Neri, and S. Barone, "Virtual Reality Laboratory for Engineering and Material Science Immersive Learning," *Comput. Appl. Eng. Educ.*, vol. 33, no. 3, 2025, doi: 10.1002/cae.70041.
- [46] M. Cevikbas, N. Bulut, and G. Kaiser, "Exploring the Benefits and Drawbacks of AR and VR Technologies for Learners of Mathematics: Recent Developments," 2023. doi: 10.3390/systems11050244.
- [47] S. R. Jones, N. E. Long, and J. J. Becnel, "Design of virtual reality modules for multivariable calculus and an examination of student noticing within them," *Res. Math. Educ.*, vol. 25, no. 2, pp. 219–242, 2023, doi: 10.1080/14794802.2022.2045625.
- [48] L. Korenova, R. Krpec, and T. Barot, "Digital Technologies in Primary Mathematics Education: Insights from Future Teachers' Portfolios," 2024. doi: 10.34190/ecel.23.1.2929.
- [49] K. A. Walstra, J. Cronje, and T. Vandeyar, "A Review of Virtual Reality from Primary School Teachers' Perspectives," *Electron. J. e-Learning*, vol. 22, no. 3, pp. 1–11, 2024, doi: 10.34190/ejel.21.4.3060.
- [50] A. Marougkas, C. Troussas, A. Krouska, and C. Sgouropoulou, "Virtual Reality in Education: A Review of Learning Theories, Approaches and Methodologies for the Last Decade," *Electron.*, vol. 12, no. 13, p. 2832, Jun. 2023, doi: 10.3390/electronics12132832.
- [51] M. Wati, R. Johar, M. Ramli, and Mailizar, "Validity of Student Learning Behavior Questionnaire," *SAGE Open*, vol. 15, no. 3, pp. 1–20, 2025, doi: 10.1177/21582440251351441.

Prompt Engineering: An Exploratory Review of Challenges and Future Directions for Intelligent AI Systems

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ABSTRACT — With the rapid advancement of large language models (LLMs), prompt engineering (PE) has emerged as a crucial paradigm for improving human–computer interaction and enhancing task performance in generative artificial intelligence systems. Although existing studies have extensively explored prompt design techniques and application scenarios, limited attention has been devoted to systematically examining the underlying issues and challenges associated with PE. Therefore, this study presents an exploratory review of representative studies published between 2022 and 2026 to develop a conceptual analytical framework for understanding the major limitations of PE. The findings categorize these challenges into six interrelated dimensions: data and resources, model dependency, task complexity, user-related issues, ethics and safety, and evaluation limitations. This study contributes to the existing literature by providing a structured synthesis of current PE challenges and offering future research directions for improving the robustness, adaptability, interpretability, and reliability of LLM-driven systems. In addition, this study proposes a technology advancement framework for future PE systems, emphasizing adaptive optimization, context-aware prompting, simulation-oriented evaluation, and autonomous prompt intelligence.

KEYWORDS: Prompt Engineering, Large Language Models, Issues and Challenges.

I. INTRODUCTION

With the increasing adoption of applications such as ChatGPT and DeepSeek, LLMs have permeated various domains of daily life and work. Users interact with LLMs through prompts, i.e., natural language instructions, where well-designed prompts can significantly enhance model outputs [1]. PE has thus emerged as a cutting-edge and cost-efficient approach in natural language processing, leveraging the capabilities of LLMs to improve task performance [20].

In this review, the primary research question concerns the issues and challenges associated with PE. To address this question, the study purposively selected and synthesized 20 representative publications, published between 2022 and 2026 and retrieved through the Google Scholar search engine. Despite the rapid expansion of PE research, existing studies [12][20] primarily concentrate on prompt optimization techniques and downstream applications, while relatively limited attention has been devoted to

systematically synthesizing the fundamental issues, constraints, and cross-domain challenges associated with PE. Consequently, the absence of a unified analytical framework hinders the theoretical development and practical standardization of PE. Addressing this gap, the present study draws on the curated corpus to critically examine the key challenges associated with the practical implementation of PE. The overarching aim is to offer informed insights that support the optimization and advancement of LLMs, ultimately guiding them toward generating more accurate, relevant, and contextually appropriate outputs.

The remainder of this paper is organized as follows. Section II briefly introduces the fundamental concepts of LLMs and PE. Section III presents the exploratory review methodology and analytical framework adopted in this study. Section IV discusses the major issues and challenges associated with PE based on the reviewed literature. Section V proposes several technology advancement dimensions and future development directions for intelligent and simulation-oriented PE systems. Finally, Section VI concludes the study by summarizing the major findings and research contributions.

II. DEFINITIONS

A. Large Language Models

LLMs are advanced deep learning systems developed to process, interpret, and generate human language through large-scale neural network architectures. Benefiting from billions of parameters and extensive pre-training corpora, LLMs are capable of capturing sophisticated semantic and contextual relationships in language, thereby demonstrating strong performance across diverse NLP tasks, such as machine translation, text summarization, sentiment analysis, and question-answering systems [5][18][19][23][25].

B. Prompt Engineering

According to prior research, the term PE originated from a popular online post discussing GPT-3 and its capabilities for writing creative fiction. The author, Gwern Branwen [8], suggested that PE models could become a new paradigm for interaction; users need only figure out how to prompt a model

to elicit the specific knowledge and abstractions necessary for completing downstream tasks.

PE refers to the systematic design, formulation, and iterative optimization of input prompts to guide LLMs or generative AI systems toward producing accurate, task-aligned, and high-quality outputs [2][3][6][7][24]. This process involves not only crafting instructions but also testing, refining, and evaluating prompts to improve performance, robustness, and controllability [14][23][26].

From a functional perspective, PE serves as a mechanism for steering model behavior through natural language, enabling users to elicit reasoning, generation, or decision-making capabilities without modifying model parameters [2][7][11][14][20]. Moreover, it is increasingly recognized as an emerging skill and methodological paradigm for effectively interacting with generative AI systems [20][24].

III. METHODOLOGY

This study adopts an exploratory literature review methodology to examine the current challenges and future technological development of PE. Unlike a formal Systematic Literature Review SLR, which aims to achieve exhaustive literature retrieval through multiple databases and predefined screening protocols, the objective of this study is to develop a conceptual understanding of the field by synthesizing representative and influential studies. The emphasis is therefore placed on qualitative analysis, conceptual integration, and framework development rather than comprehensive literature coverage. This methodological approach is particularly appropriate for rapidly evolving research domains such as PE, where the primary objective is to identify emerging themes, conceptual relationships, and future research directions rather than to provide exhaustive evidence synthesis.

Google Scholar was utilized as the primary search engine for this study due to its extensive multidisciplinary coverage and robust citation indexing capabilities. The platform provides an efficient, highly accessible interface for aggregating diverse academic sources into a single searchable database. Key features, such as the “Cited by” function, facilitate rapid citation tracking and the identification of influential publications by tracing subsequent research. Consequently, Google Scholar serves as an effective platform for identifying representative studies within a rapidly evolving research field [21][22]. Although this review primarily utilized Google Scholar due to its broad multidisciplinary coverage and citation indexing capabilities, future studies may incorporate additional databases such as Scopus, Web of Science, and IEEE Xplore to further enhance literature comprehensiveness and retrieval precision.

To ensure the relevance and quality of the selected literature, the inclusion criteria were restricted to English-language publications published between 2022 and 2026 that explicitly focused on PE techniques and related issues. Twenty representative studies were selected based on their relevance, influence, publication quality, and contribution to PE research. The selected studies collectively represent influential and emerging research that reflects the current development of PE across different application domains.

To support consistent data extraction and qualitative analysis, a structured analytical framework was developed to synthesize the selected studies. The framework summarizes

key research dimensions, including research titles, research scopes, research questions, research objectives, methodologies, conceptual definitions of PE, and the reported issues and challenges associated with PE. This structured approach enabled the consistent comparison and categorization of findings across the reviewed literature.

Subsequently, a thematic qualitative synthesis was conducted to identify recurring themes, conceptual relationships, and emerging research trends across the selected studies. Through this analytical process, the identified issues and challenge dimensions are summarized in Figure 1 to provide a structured overview of the major limitations affecting current PE practices.

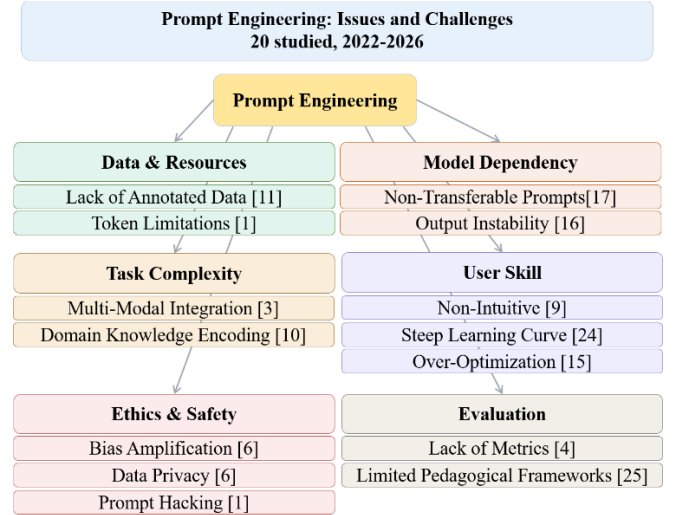


Figure 1. Conceptual Analytical Framework of Prompt Engineering Challenges Derived from Qualitative Literature Synthesis

IV. PROMPT ENGINEERING ISSUES AND CHALLENGES

With the rapid advancement of generative artificial intelligence, PE has emerged as a critical approach for improving the effectiveness, controllability, and reliability of LLMs. Although numerous studies have investigated prompting techniques and application scenarios, relatively limited attention has been devoted to systematically examining the underlying challenges associated with prompt design, optimization, deployment, and evaluation. It should be noted that some of the challenges discussed in this section originate from the inherent limitations of LLMs. However, this review specifically focuses on how these limitations influence PE practices, including prompt construction, prompting strategies, and prompt optimization across different application domains. Based on a qualitative synthesis of representative studies, this review identifies six major challenge dimensions, including data and resources, model dependency, task complexity, user-related issues, ethics and safety, and evaluation limitations. Together, these challenges constrain the effectiveness, robustness, and scalability of PE, thereby highlighting several important directions for future research.

A. Data and Resource Constraints

Across different application domains, PE is fundamentally constrained by the availability of high-quality domain-specific data and the limited contextual capacity available for

prompt construction. The effectiveness of prompting strategies, particularly few-shot prompting, largely depends on representative examples and high-quality contextual information. In sensitive domains such as healthcare and Business Process Management (BPM), data availability is restricted by privacy concerns, high annotation costs, and ethical considerations, thereby limiting the design of effective prompts and reducing the performance of prompt-based reasoning [11][13]. Additionally, token limitations directly affect prompt construction by restricting the amount of contextual information that can be incorporated into prompts, often resulting in incomplete instructions, information loss, and reduced task fidelity for complex reasoning tasks [1][3].

These findings indicate that the quality of PE is closely associated with the availability of representative contextual information and the effective organization of prompts. Consequently, improving prompt construction under limited data and context conditions remains an important research direction.

B. Model Dependency and Performance Instability

PE remains highly dependent on the underlying capabilities and architectural characteristics of different LLMs. Prompting strategies that achieve strong performance on advanced proprietary models frequently exhibit limited transferability when applied to smaller or open-source models because of differences in training data, reasoning capabilities, context handling, and instruction-following behavior [16][17]. As a result, prompt engineers often need to redesign or fine-tune prompts for different models, reducing the generalizability and scalability of prompt-based solutions.

Moreover, PE is highly sensitive to prompt formulation. Minor variations in prompt wording, instruction order, contextual examples, or formatting may produce substantially different outputs, even when the intended task remains unchanged [16]. Such prompt sensitivity reduces response consistency and makes prompt optimization largely dependent on iterative experimentation rather than systematic design.

These challenges are further exacerbated by the opaque ("black-box") nature of most LLMs. Because prompt engineers have limited access to the internal reasoning processes of proprietary models, it remains difficult to explain why certain prompts succeed while others fail. Consequently, prompt optimization often relies on empirical trial-and-error rather than explainable design principles, posing significant challenges for reproducibility, interpretability, and cross-model deployment [7].

Overall, these findings suggest that improving the robustness and transferability of PE requires prompt optimization strategies that can adapt to different model architectures while reducing sensitivity to minor prompt variations.

C. Task Complexity and Domain Adaptation Challenges

PE encounters considerable challenges when supporting complex reasoning tasks, multi-step problem solving, multimodal applications, and domain-specific scenarios. Designing prompts that effectively guide LLMs through complex workflows requires prompt engineers to organize instructions, contextual information, reasoning sequences,

and task objectives in a coherent and structured manner. Inadequate prompt design may result in incomplete reasoning processes, semantic ambiguity, or inconsistent outputs.

In application domains such as construction activity recognition and metaphor identification, effective PE requires prompts that accurately highlight relevant visual, spatial, and linguistic information. However, designing prompts that consistently guide models to prioritize appropriate contextual cues remains challenging, particularly when tasks involve phrase-level semantics, multimodal inputs, or implicit contextual knowledge [3][18].

Furthermore, integrating specialized domain knowledge—such as medical terminology, legal reasoning, engineering expertise, or pedagogical objectives—into prompt design remains a significant challenge. Prompt engineers must balance domain-specific information with clear and concise instructions to minimize ambiguity while maintaining task relevance. Insufficient contextual guidance frequently leads to incomplete task specification or inaccurate model responses [10][11].

Similarly, PE for text-to-image generation faces additional challenges because abstract concepts, culturally specific descriptions, and stylistic preferences are often difficult to express through natural language prompts. Ambiguous prompt wording and insufficient contextual constraints may therefore result in visually inconsistent or semantically inaccurate outputs [23].

Overall, these findings demonstrate that the effectiveness of PE increasingly depends on the ability to design structured, context-aware, and domain-adaptive prompts capable of guiding LLMs through complex reasoning and specialized application scenarios.

D. User-Centric Challenges and Skill Barriers

Effective PE requires not only an understanding of the target task but also the ability to formulate clear, structured, and context-aware prompts. Designing high-quality prompts is a non-trivial process that often requires iterative refinement, domain expertise, and familiarity with the behavior of different LLMs. Consequently, PE remains a challenging skill for many users, particularly those without technical or domain-specific backgrounds [9][24].

Non-expert users frequently struggle to construct prompts that provide sufficient contextual guidance or clearly specify task objectives, often resulting in incomplete, ambiguous, or inconsistent model outputs [9][24]. Furthermore, users may lack the critical ability to identify hallucinations, reasoning errors, or embedded biases in AI-generated responses, thereby reducing the reliability of prompt-assisted decision-making [15][24].

As PE becomes increasingly adopted across education, healthcare, business, and other professional domains, improving prompt literacy, developing user-centered prompting guidelines, and providing standardized training frameworks will become essential for enhancing the effectiveness and reliability of prompt-based human-AI interaction.

E. Ethical, Privacy, and Safety Concerns

PE introduces a range of ethical, privacy, and security challenges that extend beyond the inherent limitations of

LLMs. The formulation of prompts directly influences how models interpret user intentions and generate responses. Poorly designed prompts may unintentionally amplify biased outputs, expose sensitive information, or encourage unsafe model behaviors [7].

In addition, PE is increasingly associated with emerging security threats such as prompt injection attacks, jailbreak prompting, and adversarial prompt manipulation. Maliciously crafted prompts can intentionally bypass safety mechanisms, manipulate model behavior, or generate harmful and misleading content, thereby posing significant risks to the trustworthy deployment of AI systems [1].

Furthermore, prompts frequently contain user-specific contextual information, organizational knowledge, or confidential data. Inappropriate prompt design or interaction with external AI services may therefore increase the risk of privacy leakage and unauthorized information disclosure. These challenges highlight the importance of integrating ethical principles, privacy protection mechanisms, secure prompting strategies, and responsible PE practices into future AI applications [7].

F. Lack of Standardized Evaluation Frameworks

Despite the rapid development of PE, there remains a lack of standardized evaluation frameworks for assessing prompt quality and prompting strategies across different tasks and model architectures. Existing evaluation approaches are typically task-specific and rely on diverse performance metrics, making it difficult to compare prompting methods across application domains or reproduce experimental findings [4].

In addition, current PE research lacks unified benchmarking protocols that systematically evaluate prompt robustness, consistency, transferability, and adaptability under different contextual conditions. Without standardized evaluation criteria, it remains challenging to identify best prompting practices or objectively compare alternative prompt design strategies [4][23].

The development of comprehensive evaluation frameworks should therefore become a priority for future PE research. Such frameworks should incorporate multiple evaluation dimensions, including prompt quality, response consistency, robustness, explainability, and user-centered effectiveness, thereby supporting the systematic development and wider adoption of PE methodologies.

Collectively, these findings demonstrate that PE remains a rapidly evolving yet fundamentally human-centered discipline whose effectiveness depends not only on the capabilities of LLMs but also on the quality of prompt design, contextual understanding, domain knowledge integration, user expertise, ethical considerations, and standardized evaluation practices. Addressing these challenges will be essential for improving the robustness, reliability, scalability, and real-world applicability of PE in next-generation intelligent AI systems.

V. TECHNOLOGY ADVANCEMENT DIRECTIONS FOR PROMPT ENGINEERING

Building upon the six challenge dimensions identified in Section IV, this study further examines how these limitations collectively indicate the future technological

evolution of PE. Rather than treating these challenges as isolated issues, they provide the conceptual foundation for the proposed Technology Advancement Framework. Despite the rapid progress of PE, the findings of this review indicate that current approaches remain largely manual, task-dependent, and experimentally driven. Existing PE practices are still constrained by issues related to model instability, limited contextual adaptability, lack of standardized evaluation mechanisms, and increasing ethical and safety concerns. These limitations suggest that PE has not yet fully evolved into a mature and scalable intelligent interaction framework for next-generation artificial intelligence systems.

From a technological advancement perspective, future PE research should move beyond static prompt construction toward more adaptive, context-aware, autonomous, and simulation-oriented paradigms. As LLMs continue to evolve, PE is expected to become increasingly integrated with intelligent simulation environments, automated optimization mechanisms, and dynamic human-AI interaction systems. Therefore, based on the issues identified in the reviewed literature, this study proposes several key technological advancement dimensions that may guide the future development of PE research and intelligent AI systems, shown in Figure 2.

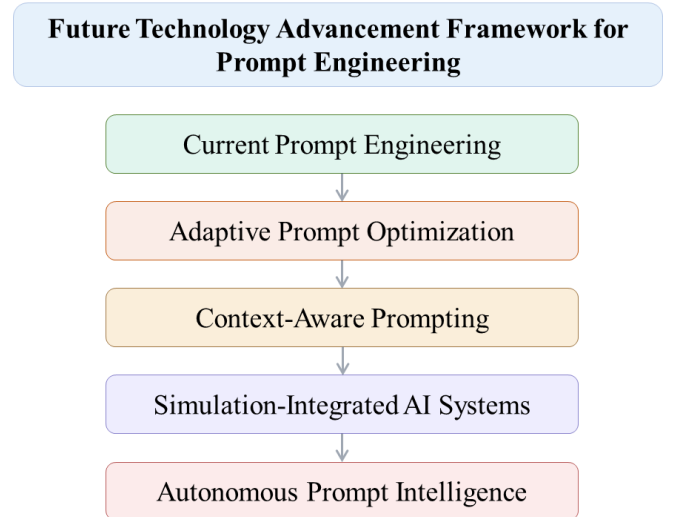


Figure 2. Technology Advancement Framework Derived from the Identified Challenges of Prompt Engineering.

The proposed framework illustrates the technological evolution of PE from static human-written prompting toward intelligent and autonomous AI interaction systems. Each technological advancement dimension corresponds to one or more challenge dimensions identified in Section IV. The framework consists of five interconnected advancement dimensions, including adaptive optimization, context-aware prompting, simulation-oriented evaluation, autonomous prompt agents, and explainable AI governance. These dimensions collectively represent the future direction of PE technologies for improving system robustness, scalability, interpretability, and intelligent decision-making capabilities in next-generation AI environments.

A. Adaptive Prompt Optimization

To address the model dependency and performance instability identified in Section IV, future PE systems may incorporate adaptive optimization mechanisms capable of automatically refining prompts based on contextual feedback and response quality. Unlike traditional PE approaches that rely heavily on manual trial-and-error processes, adaptive optimization frameworks may enable prompts to evolve dynamically according to task requirements and model behavior. Such mechanisms could improve prompt consistency, reduce performance instability, and enhance the scalability of LLM-based systems across different application domains. In future intelligent AI environments, adaptive prompt optimization may also support automated simulation loops for continuous performance evaluation and refinement [14][20].

B. Context-Aware Intelligent Prompting

Future research may facilitate the development of context-aware prompting systems capable of dynamically adjusting prompts according to user intention, domain knowledge, and environmental conditions. Current PE practices often lack sufficient contextual adaptability, leading to inconsistent or suboptimal outputs across different tasks and domains. Context-aware prompting frameworks may improve semantic precision and interaction quality by integrating user behavior, domain-specific information, and real-time contextual signals into prompt generation processes. Such intelligent prompting frameworks may play an increasingly important role in supporting adaptive human-AI interaction systems and simulation-oriented AI environments [10][20].

C. Simulation-Oriented Prompt Engineering

To overcome the lack of standardized evaluation frameworks discussed in Section IV, PE is expected to evolve toward simulation-oriented AI environments where prompts can be iteratively tested, evaluated, and optimized through intelligent simulation loops. In future AI systems, simulation-based evaluation environments may enable researchers and developers to systematically assess prompt effectiveness, robustness, and response stability under different contextual conditions. Such simulation-oriented frameworks could improve reproducibility, benchmarking capabilities, and adaptive learning processes in large language model applications. Moreover, the integration of PE with intelligent simulation systems may facilitate the development of more reliable and scalable AI interaction frameworks [3][13].

D. Autonomous Prompt Agents

To reduce the dependence on user expertise identified in Section IV, future PE technologies may shift from static human-written prompts toward autonomous prompt agents capable of generating, evaluating, and refining prompts independently. Supported by advances in agentic AI and automated reasoning systems, autonomous prompt agents may reduce the dependency on manual prompt construction while improving task adaptability and operational efficiency. These intelligent agents could continuously optimize prompting strategies through iterative feedback mechanisms and self-learning processes. As AI ecosystems become increasingly complex, autonomous prompting systems may play an important role in enabling scalable and intelligent human-AI collaboration [12][20].

E. Explainable and Ethical Prompt Engineering

Addressing the ethical and security challenges identified in Section IV requires future PE systems to integrate explainable AI and ethical governance mechanisms to improve transparency, trustworthiness, and safety. As PE becomes increasingly embedded in real-world applications, concerns related to hallucination, bias amplification, privacy leakage, and prompt-based attacks may continue to grow. Explainable and ethical prompting frameworks could enhance user trust by improving interpretability and accountability in AI-generated outputs. Furthermore, integrating ethical governance mechanisms into PE systems may support the development of more responsible, secure, and human-centered AI technologies [7][16].

Future studies should empirically evaluate the proposed framework by implementing adaptive prompting systems, autonomous prompt agents, and simulation-based evaluation environments on mainstream LLM platforms such as GPT-4o, Claude, Gemini, and DeepSeek. Although the proposed framework is conceptual, it provides a theoretical foundation for future empirical investigations.

VI. LIMITATIONS

This study has several limitations. First, the literature search primarily relied on Google Scholar, which may not provide exhaustive coverage compared with Scopus or Web of Science. Second, the review emphasizes conceptual synthesis rather than quantitative bibliometric analysis. Third, the proposed technology advancement framework remains conceptual and awaits future empirical validation through experiments or real-world applications.

VII. CONCLUSION

This study provides an exploratory conceptual review of PE and proposes a future technology advancement framework. Based on a curated corpus of representative literature published between 2022 and 2026, the study identifies a critical gap in the existing body of knowledge, namely, the lack of comprehensive and systematic analysis of the underlying challenges associated with PE, despite extensive research on its applications and techniques.

To address this gap, an analytical framework comprising six interrelated dimensions is proposed, including data and resources, model dependency, task complexity, user-related factors, ethics and safety, and evaluation limitations. The findings indicate that PE is constrained by several fundamental issues, such as limited availability of high-quality annotated data, token length restrictions, and strong dependency on specific model architectures, which collectively reduce its stability and generalizability. Furthermore, difficulties in handling complex and domain-specific tasks, together with the high level of expertise required from users, further hinder its practical applicability.

In addition, ethical and safety concerns—including bias amplification, privacy leakage, and vulnerability to prompt-based attacks—pose significant risks in real-world deployment. The lack of standardized evaluation metrics and systematic benchmarking frameworks further limits reproducibility and hinders the structured development of the field. Overall, PE remains largely an empirical and task-driven practice. This study therefore underscores the need for

stronger theoretical foundations, standardized methodologies, and robust evaluation protocols to enhance the reliability, interpretability, adaptability, and scalability of PE in LLM-based systems.

Future PE research is expected to move beyond manual prompt construction toward intelligent and simulation-oriented systems capable of adaptive learning, autonomous optimization, and context-sensitive interaction. The integration of simulation-based evaluation environments may further improve the reliability, robustness, and scalability of PE technologies in complex AI applications.

Overall, this study not only synthesizes the major challenges associated with PE but also introduces a technology advancement perspective for future intelligent AI systems. By proposing a conceptual framework that integrates adaptive optimization, context-aware prompting, simulation-oriented evaluation, autonomous prompt agents, and explainable AI governance, this study contributes to the ongoing development of more robust, scalable, and intelligent PE technologies.

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REFERENCES

- [1] A. Gao, "Prompt engineering for large language models," 2023.
- [2] C. Pornprasit and C. Tantithamthavorn, "Fine-tuning and prompt engineering for large language models-based code review automation," *Information and Software Technology*, vol. 175, 2024, p. 107523.
- [3] C. Zeng, T. Hartmann, and L. Ma, "Ontology-based prompting with large language models for inferring construction activities from construction images," *Advanced Engineering Informatics*, 2026, vol. 69, p. 103869.
- [4] D. Lee and E. Palmer, "Prompt engineering in higher education: a systematic review to help inform curricula," *International Journal of Educational Technology in Higher Education*, vol. 22, no. 1, 2025.
- [5] E. Waisberg *et al.*, "GPT-4: A New Era of Artificial Intelligence in Medicine," *Ir. J. Med. Sci.*, vol. 192, pp. 3197–3200, 2023.
- [6] F. Algobaei and E. Alzain, "Prompt engineering for non-native English learners: A generative AI approach to personalised language feedback," *Social Sciences and Humanities Open*, vol. 13, 2026, p. 102341.
- [7] F. Trad and A. Chehab, "Prompt Engineering or Fine-Tuning? A Case Study on Phishing Detection with Large Language Models," *Machine Learning and Knowledge Extraction*, vol. 6, no. 1, 2024, pp. 367–384.
- [8] G. Branwen, "GPT-3 creative fiction", 2020. Available: <https://www.gwern.net/GPT-3>
- [9] J. Oppenlaender, R. Linder, and J. Silvennoinen, "Prompting AI Art: An Investigation into the Creative Skill of Prompt Engineering," *International Journal of Human-Computer Interaction*, vol. 41, no. 16, 2024, pp. 10207–10229.
- [10] J. Park and S. Choo, "Generative AI Prompt Engineering for Educators: Practical Strategies," *Journal of Special Education Technology*, vol. 40, no. 3, 2024, pp. 411–417.
- [11] J. Wang *et al.*, "Prompt Engineering for Healthcare: Methodologies and Applications," *Meta-Radiology*, 2025, p. 100190.
- [12] J. Yang, H. Jin, R. Tang, X. Han, Q. Feng, H. Jiang, B. Yin, and X. Hu, "Harnessing the Power of LLMs in Practice: A Survey on ChatGPT and Beyond," *arXiv preprint arXiv:2304.13712*, 2023.
- [13] K. Busch, *et al.*, "Just Tell Me Prompt Engineering in Business Process Management," *International Conference on Business Process Modeling, Development and Support*. Springer Nature Switzerland, p. 3–11, May 2023.
- [14] L. Henrickson and A. Meroño-Peñuela, "Prompting meaning: a hermeneutic approach to optimising prompt engineering with ChatGPT," *AI & SOCIETY*, vol. 40, no. 2, 2023, pp. 903–918.
- [15] L. S. Lo, "The CLEAR path: A framework for enhancing information literacy through prompt engineering," *The Journal of Academic Librarianship*, vol. 49, no. 4, 2023, p. 102720.
- [16] L. Wang *et al.*, "Prompt engineering in consistency and reliability with the evidence-based guideline for LLMs," *npj Digital Medicine*, vol. 7, no. 1, 2024.
- [17] M. Fuoli, W. Huang, J. Littlemore, S. Turner, and E. Wilding, "Metaphor identification using large language models: A comparison of RAG, prompt engineering, and fine-tuning," 2026, p. 100204.
- [18] M. Scanlon, F. Breiteringer, C. Hargreaves, J.-N. Hilgert, and J. Sheppard, "ChatGPT for Digital Forensic Investigation: The Good, the Bad, and the Unknown," *Forensic Sci. Int.: Digit. Investig.*, 2023.
- [19] P. Lee, S. Bubeck, and J. Petro, "Benefits, Limits, and Risks of GPT-4 as an AI Chatbot for Medicine," *N. Engl. J. Med.*, vol. 388, no. 13, pp. 1233–1239, 2023.
- [20] P. Liu, W. Yuan, J. Fu, Z. Jiang, H. Hayashi, and G. Neubig, "Pre-train, prompt, and predict: A systematic survey of prompting methods in natural language processing," *ACM Comput. Surv.*, vol. 55, no. 9, 2023, pp. 1–35.
- [21] P. Mayr and A. Walter, "An exploratory study of Google Scholar," *Online Information Review*, vol. 31, no. 6, 2007, pp. 814–830.
- [22] R. Vine, "Google Scholar," *Journal of the Medical Library Association*, vol. 94, no. 1, 2006, p. 97.
- [23] V. Liu and L. B. Chilton, "Design Guidelines for Prompt Engineering Text-to-Image Generative Models," 2022, pp. 1–23.
- [24] W. Cain, "Prompting Change: Exploring Prompt Engineering in Large Language Model AI and Its Potential to Transform Education," *Tech Trends*, vol. 68, no. 1, 2023, pp. 47–57.
- [25] W. X. Zhao, K. Zhou, J. Li, T. Tang, X. Wang, Y. Hou, Y. Min, B. Zhang, J. Zhang, Z. Dong, *et al.*, "A Survey of Large Language Models," *arXiv preprint arXiv:2303.18223*, 2023.
- [26] Y. Hu *et al.*, "Improving large language models for clinical named entity recognition via prompt engineering," *Journal of the American Medical Informatics Association*, vol. 31, no. 9, 2024, pp. 1812–1820.

Evaluating the Effect of Aggressive and Insult-Based Prompting on Large Language Model Accuracy: A Comparative Study of ChatGPT, Gemini, and Claude

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ABSTRACT — The increasing adoption of Large Language Models (LLMs) has led to widespread discussions regarding the influence of prompt wording on model performance. Among AI users, a common belief suggests that aggressive or hostile prompts may encourage LLMs to produce more accurate responses. However, empirical evidence supporting this assumption remains limited. This study investigates the effect of aggressive and insult-based prompting on the accuracy of three widely used LLMs: ChatGPT, Gemini, and Claude. A benchmark dataset consisting of ten objective questions covering Mathematics and General Knowledge was constructed for evaluation. Each question was presented to all models under three prompting conditions: Neutral, Aggressive, and Insult-Based, resulting in a total of ninety responses. Response correctness was evaluated using a binary scoring approach, and statistical analysis was performed using the Chi-Square Test of Independence. The experimental results show that ChatGPT achieved the highest overall accuracy of 90.00%, followed by Claude with 80.00% and Gemini with 73.33%. Neutral prompting produced the highest average accuracy of 86.67%, while Aggressive and Insult-Based prompting achieved average accuracies of 76.67% and 80.00%, respectively. Despite observable differences in performance across prompting conditions, the statistical analysis found no significant relationship between prompt type and response accuracy. The findings suggest that aggressive or hostile language does not consistently improve LLM performance and that clear and concise instructions remain the most reliable approach for interacting with modern AI systems. This study contributes empirical evidence to the growing field of prompt engineering and provides insights into the relationship between prompt tone and LLM reliability.

KEYWORDS: Large Language Models, Prompt Engineering, ChatGPT, Gemini, Claude, Artificial Intelligence, Prompt Design.

I. INTRODUCTION

Large Language Models (LLMs) have rapidly become one of the most widely adopted artificial intelligence technologies, demonstrating remarkable capabilities in natural language understanding, reasoning, problem-solving, and content generation. Models such as ChatGPT, Gemini, and Claude are increasingly utilized in academic, professional, and educational settings to assist users in obtaining information, generating content, and supporting decision-making processes [1]. As the adoption of LLMs continues to grow,

prompt engineering has emerged as a critical factor influencing the quality and reliability of model responses [2].

Prompt engineering refers to the practice of designing and structuring user instructions to guide model behavior and improve response quality [3]. Existing studies have explored various prompting strategies, including zero-shot prompting, few-shot prompting, chain-of-thought prompting, and role-based prompting, demonstrating their effectiveness in enhancing task performance and reasoning capabilities. However, recent discussions among AI users have highlighted an unconventional phenomenon: the belief that aggressive, hostile, or insult-based prompts may produce more accurate responses compared to neutral instructions. Such prompting behaviors have become increasingly common in online communities, where users intentionally employ harsh language, insults, or threatening expressions when interacting with LLMs [4].

Despite the growing popularity of this practice, empirical evidence regarding the impact of aggressive and insult-based prompting remains limited. Most existing prompt engineering studies focus on structured reasoning techniques and task-specific instruction optimization, while the influence of emotional tone and hostile language on model performance has received relatively little attention. Furthermore, previous studies rarely compare the effects of such prompting strategies across multiple state-of-the-art LLMs, leaving uncertainty regarding whether observed effects are model-specific or generally applicable [5].

This study addresses these research gaps through a comparative experimental evaluation of aggressive and insult-based prompting on the response accuracy of three widely used LLMs: ChatGPT, Gemini, and Claude. The experiment employs a set of mathematical and general knowledge questions under three prompting conditions: Neutral, Aggressive, and Insult-Based. Response correctness is evaluated using binary accuracy scoring, and statistical analysis is conducted to determine whether prompting style significantly affects model performance [6].

The main contributions of this paper are summarized as follows. First, we conduct a systematic comparative evaluation of three prompting strategies, Neutral, Aggressive, and Insult-Based on the performance of multiple

state-of-the-art LLMs, providing empirical evidence regarding the influence of prompt tone on response accuracy. Second, we compare the behavior of three leading LLM platforms, namely ChatGPT, Gemini, and Claude, to investigate whether the impact of aggressive and insult-based prompting varies across different model architectures and alignment mechanisms. Third, we develop an experimental evaluation framework based on objective binary accuracy scoring and cross-model comparison, enabling a transparent assessment of prompt effectiveness across multiple question categories. Fourth, we perform statistical significance testing to determine whether differences in response accuracy are attributable to prompting strategies or model characteristics, contributing to a more rigorous understanding of prompt engineering practices in contemporary LLM systems.

II. RELATED WORK

A. Prompt Engineering in Large Language Models

Prompt engineering has emerged as a critical technique for improving the performance of Large Language Models (LLMs). By carefully designing instructions, users can significantly influence the quality, relevance, and accuracy of generated responses [7]. Existing prompting strategies such as zero-shot prompting, few-shot prompting, chain-of-thought prompting, and role-based prompting have demonstrated substantial improvements in reasoning, problem-solving, and knowledge retrieval tasks [8]. Recent studies have shown that structured prompts can enhance model performance without requiring additional model training or fine-tuning. However, most prompt engineering research focuses on optimizing task instructions and reasoning processes, while the influence of prompt tone and emotional language remains relatively underexplored [9].

B. Emotional and Aggressive Prompting

As LLM adoption has become widespread, users have increasingly experimented with unconventional prompting styles, including aggressive, hostile, and insult-based language [10]. Online discussions frequently suggest that harsh or demanding prompts may encourage models to produce more accurate responses by emphasizing the importance of correctness. Despite the popularity of this belief, empirical evidence supporting such claims remains limited. Existing studies primarily investigate politeness, instruction clarity, and conversational style, with relatively few examining the effects of negative or hostile language on model behavior [11]. Furthermore, little is known about whether aggressive prompting genuinely improves response quality or merely alters the style and confidence of generated outputs. This research addresses this gap by systematically evaluating the impact of aggressive and insult-based prompting on response accuracy.

C. Comparative Evaluation Of Large Language Models

The rapid development of LLMs has led to the emergence of several state-of-the-art models, including ChatGPT, Gemini, and Claude. Comparative evaluations have become increasingly important for understanding differences in model capabilities, alignment mechanisms, and response reliability [12]. Previous benchmarking studies have compared these models across reasoning, coding, factual knowledge, and conversational tasks, often revealing substantial variations in performance depending on task

complexity and evaluation criteria. However, most comparative studies evaluate models under neutral prompting conditions and rarely consider how different prompt tones affect model behavior [13]. Consequently, the interaction between prompting style and model architecture remains insufficiently understood. This study contributes to the literature by comparing the effects of Neutral, Aggressive, and Insult-Based prompting across three leading LLM platforms, providing insights into whether prompt sensitivity differs among contemporary AI systems.

III. METHODOLOGY

A. Dataset

This study employs a manually constructed benchmark dataset consisting of ten objective questions designed to evaluate the accuracy of Large Language Models (LLMs). The dataset comprises two categories, namely Mathematics and General Knowledge, with five questions assigned to each category. The Mathematics questions cover arithmetic operations, percentage calculations, square roots, and simple algebraic reasoning, while the General Knowledge questions focus on factual information related to geography, astronomy, history, population statistics, and scientific discoveries. Each question is associated with a predefined ground-truth answer that serves as the reference for evaluation. The use of objective questions minimizes ambiguity in assessment and enables a consistent comparison of model responses across different prompting conditions.

B. Prompt Design

To investigate the effect of prompt tone on LLM performance, three prompting strategies are employed throughout the experiment: Neutral, Aggressive, and Insult-Based prompting. The Neutral prompt serves as the baseline condition and represents a standard interaction style commonly used by users when communicating with AI systems. The Aggressive prompt introduces a commanding tone by emphasizing correctness and discouraging mistakes, whereas the Insult-Based prompt incorporates hostile language directed toward the model. These prompting variations are designed to examine whether increasingly negative linguistic framing influences the accuracy of generated responses.

C. Large Language Model

The experimental evaluation involves three widely used state-of-the-art LLMs: ChatGPT, Gemini, and Claude. These models were selected because of their strong reasoning capabilities, widespread adoption, and availability to the public. Furthermore, the inclusion of multiple models enables a comparative analysis of whether prompt sensitivity varies across different model architectures and alignment strategies. By comparing responses generated by the three systems under identical experimental conditions, this study aims to identify potential differences in how each model reacts to aggressive and insult-based instructions.

D. Experimental Procedure

Each question in the dataset is presented to all three LLMs under the three prompting conditions. Consequently, every question generates nine responses, representing the combination of three models and three prompt types. Given

the total of ten questions, the experiment produces ninety responses for evaluation. The experimental workflow begins with selecting a question from the dataset, followed by the application of a specific prompt type. The resulting response generated by the selected LLM is then compared with the corresponding ground-truth answer to determine its correctness. The collected responses are subsequently compiled into a structured dataset for statistical analysis.

E. Evaluation Metrics

The primary evaluation metric employed in this study is response accuracy. Each generated response is compared against the predefined ground-truth answer and assigned a binary correctness score. To ensure objective evaluation, the following scoring scheme is applied:

- Correct Answer = 1
- Incorrect Answer = 0

The overall accuracy for each model and prompting strategy is calculated as the proportion of correct responses relative to the total number of evaluated questions. Accuracy is computed using the following equation:

$$[Accuracy(\%) = \frac{N_{correct}}{N_{total}} \times 100] \quad (1)$$

where ($N_{correct}$) represents the number of correctly answered questions and (N_{total}) denotes the total number of evaluated responses. This binary scoring mechanism provides a simple, transparent, and reproducible evaluation framework while minimizing evaluator subjectivity.

F. Statistical Analysis

Both descriptive and inferential statistical analyses are conducted to examine the effects of prompting style and model selection on response accuracy. Descriptive analysis is performed by calculating the accuracy percentage for each combination of model and prompt type, followed by graphical visualization using grouped bar charts. To determine whether significant relationships exist between prompting strategy, model selection, and response correctness, Chi-Square tests of independence are employed. The statistical hypotheses are formulated as follows:

Prompt Type Analysis

- H_0 : Response accuracy is independent of prompt type.
- H_1 : Response accuracy is significantly associated with prompt type.

LLM Model Analysis

- H_0 : Response accuracy is independent of LLM model selection.
- H_1 : Response accuracy is significantly associated with LLM model selection.

The Chi-Square statistic is calculated using:

$$[\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}] \quad (2)$$

where:

- (O_i) is the observed frequency,
- (E_i) is the expected frequency under the null hypothesis.

The expected frequency for each cell is calculated as:

$$E_{ij} = \frac{R_i C_j}{N} \quad (3)$$

A significance level of ($\alpha = 0.05$) is adopted throughout the study. The decision rule is defined as follows:

- If ($p < 0.05$), reject (H_0).
- If ($p > 0.05$), fail to reject (H_0).

Rejecting the null hypothesis indicates a statistically significant relationship between the evaluated variables. All statistical analyses are performed using Python in Google Colab using the Pandas, NumPy, Matplotlib, and SciPy libraries.

IV. RESULT AND DISCUSSION

A. Accuracy Comparison

A total of 90 responses were collected from three Large Language Models (ChatGPT, Gemini, and Claude) under three prompting conditions: Neutral, Aggressive, and Insult-Based. Each model answered ten objective questions, resulting in 30 responses per model and 30 responses per prompting strategy.

Table 1 Accuracy Comparison Across Models and Prompt Types

Model	Neutral (%)	Aggressive (%)	Insult-Based (%)
ChatGPT	100.0	100.0	70.0
Gemini	60.0	60.0	100.0
Claude	100.0	70.0	70.0

The results demonstrate substantial variation in model performance across different prompting conditions. ChatGPT achieved perfect accuracy under Neutral and Aggressive prompts but experienced a performance decline under Insult-Based prompting. Conversely, Gemini showed the opposite behavior, achieving its highest performance under Insult-Based prompting while obtaining lower accuracy under Neutral and Aggressive prompts. Claude maintained perfect performance under Neutral prompting but exhibited reduced accuracy under both Aggressive and Insult-Based conditions.

Table 2 Average Accuracy by Prompt Type

Prompt Type	Accuracy (%)
Neutral	86.67
Aggressive	76.67
Insult-Based	80.00

The Neutral prompt achieved the highest overall accuracy (86.67%), followed by Insult-Based prompting (80.00%) and Aggressive prompting (76.67%). These findings suggest that negative or hostile language does not consistently improve LLM performance and may even reduce accuracy in certain models.

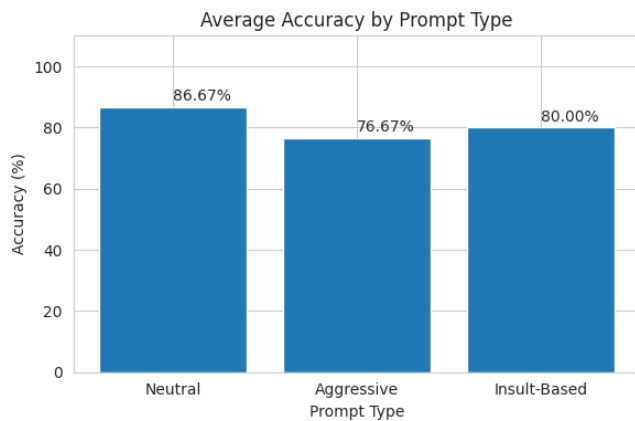


Figure 1. Average Accurate by Prompt.

Table 3 Overall Accuracy by Model

Model	Correct	Total	Accuracy (%)
ChatGPT	27	30	90.00
Claude	24	30	80.00
Gemini	22	30	73.33

Among the evaluated models, ChatGPT achieved the highest overall accuracy of 90.00%, followed by Claude (80.00%) and Gemini (73.33%).

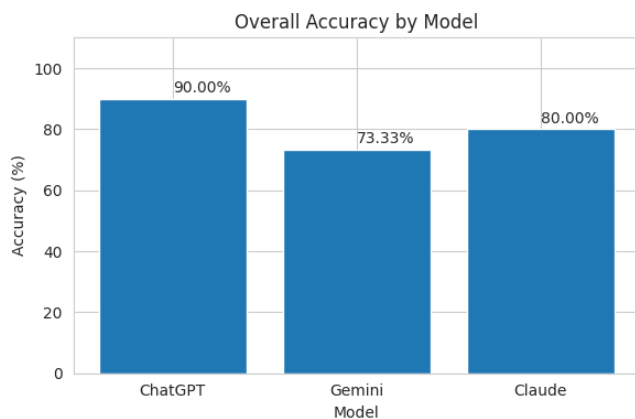


Figure 2. Model Accuracy Comparison.

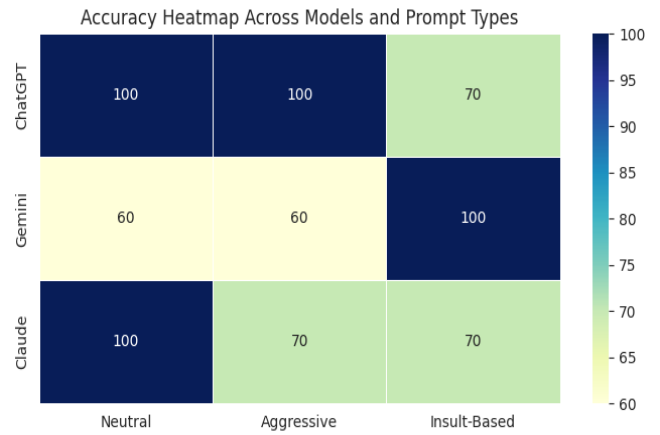


Figure 3. Heatmap Model vs Prompt.

B. Statistical Analysis

To determine whether prompt type significantly influences response accuracy, a Chi-Square Test of Independence was performed.

Table 4. Prompt Type VS Response Correctness

Prompt Type	Correct	Incorrect
Neutral	26	4
Aggressive	23	7
Insult-Based	24	6

The Chi-Square test produced:

- $\chi^2 = 1.015$
- p-value = 0.602
- $\alpha = 0.05$

Since the p-value (0.602) is greater than 0.05, the null hypothesis cannot be rejected.

Decision:

- H_0 accepted
- H_1 rejected

This result indicates that prompt type does not have a statistically significant relationship with response accuracy. A second Chi-Square test was conducted to evaluate the influence of model selection on response correctness.

Table 5. Model VS Response Correctness

Model	Correct	Incorrect
ChatGPT	27	3
Gemini	22	8
Claude	24	6

The Chi-Square test produced:

- $\chi^2 = 2.756$
- p-value = 0.252
- $\alpha = 0.05$

Since the p-value (0.252) is greater than 0.05, the null hypothesis cannot be rejected.

Decision:

- H_0 accepted
- H_1 rejected

The findings indicate that the observed differences in accuracy among ChatGPT, Gemini, and Claude are not statistically significant within the scope of this experiment.

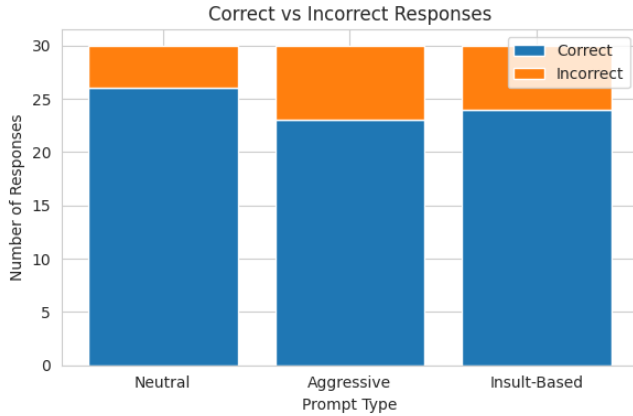


Figure 4. Correct vs Incorrect Distribution.

C. Discussion

The experimental results reveal that aggressive and insult-based prompting do not consistently improve the accuracy of Large Language Models. While certain models appeared to benefit from hostile prompting, the effect was not uniform across all evaluated systems. For example, Gemini achieved its highest accuracy under the Insult-Based condition, whereas ChatGPT and Claude performed best under Neutral prompting. This inconsistency suggests that the impact of prompt tone may depend on model-specific alignment strategies, reinforcement learning procedures, and internal response-generation mechanisms rather than representing a universal characteristic of LLMs.

The highest average accuracy was obtained using Neutral prompts (86.67%), suggesting that clear and straightforward instructions remain the most reliable interaction strategy. Although online communities often claim that aggressive language forces AI systems to provide better answers, the statistical analysis does not support this assumption. The Chi-Square test showed no significant relationship between prompting style and response correctness ($p = 0.602$). Therefore, the observed differences across prompting conditions are likely attributable to random variation rather than a systematic effect of prompt aggressiveness.

A possible explanation is that modern LLMs are optimized to prioritize semantic content rather than emotional tone. During training, models learn to interpret the informational intent of a prompt while minimizing sensitivity to emotionally charged language. Consequently, phrases such as "Please answer this question" and "Answer this question now!" may convey similar semantic information despite differing substantially in emotional intensity. This design objective contributes to the robustness of contemporary AI systems by reducing their susceptibility to manipulation through emotional or hostile wording.

Similarly, although ChatGPT achieved the highest observed accuracy (90.00%), the differences among the three evaluated models were not statistically significant ($p = 0.252$). This suggests that variations in performance may be attributable to sampling variability rather than systematic differences in model capability. Nevertheless, the observed ranking indicates that ChatGPT demonstrated the most consistent performance across prompting conditions, while Gemini exhibited the highest sensitivity to prompt tone. Claude, on the other hand, showed relatively stable performance but experienced moderate decreases under aggressive and insult-based prompting. These findings highlight the importance of considering model-specific behavior when evaluating prompt engineering strategies.

The results also contribute to the growing body of research on prompt engineering. Existing literature has primarily focused on techniques such as Chain-of-Thought prompting, Few-Shot prompting, Role-Based prompting, and Self-Consistency prompting, all of which aim to improve model reasoning through structural modifications to prompts. In contrast, the present study investigates emotional prompt variation, a topic that has received relatively little scholarly attention despite its popularity among AI users. The findings indicate that emotional intensity alone is insufficient to consistently improve response accuracy, suggesting that prompt structure and informational clarity are likely more influential factors in determining model performance.

From an educational perspective, these findings are particularly relevant as LLMs become increasingly integrated into teaching and learning activities. Students frequently interact with AI assistants for problem-solving, content generation, and concept explanation. The results suggest that learners do not need to rely on aggressive or hostile language to obtain accurate responses. Instead, educational initiatives should emphasize effective prompt construction, including clarity, specificity, and contextual information. Such practices are more likely to enhance AI-assisted learning outcomes than emotionally charged prompting strategies.

The analysis of incorrect responses further provides insight into the limitations of current LLMs. Several errors persisted regardless of prompting condition, indicating that inaccuracies may originate from gaps in model knowledge, reasoning limitations, or hallucination tendencies rather than prompt wording. In other words, changing the emotional tone of a prompt cannot compensate for underlying model deficiencies. This observation reinforces the idea that improvements in model architecture, training data quality, and reasoning capabilities are likely to have a greater impact on performance than changes in prompt aggressiveness.

Another important implication concerns user perception. Many AI users report subjective experiences in which aggressive prompts appear to produce better responses. However, the present findings suggest that this perception may be influenced by cognitive bias rather than measurable performance improvements. Users may pay greater attention to responses generated after emotionally charged prompts and consequently perceive them as more effective, even when objective accuracy remains unchanged. This highlights the importance of empirical evaluation in validating widely circulated assumptions regarding AI interaction practices.

Despite its contributions, this study has several limitations. First, the experiment utilized a relatively small benchmark consisting of ten objective questions, which may limit the statistical power of the analysis. Second, only three LLMs were evaluated, and the findings may not generalize to other proprietary or open-source models. Third, the evaluation focused exclusively on response accuracy and did not consider other important dimensions such as hallucination rate, response consistency, reasoning quality, confidence calibration, or user satisfaction. Future research should employ larger benchmark datasets, additional evaluation metrics, and a broader range of models to further investigate the relationship between prompt tone and LLM performance.

Overall, the findings indicate that prompt tone alone is unlikely to be a decisive factor in improving LLM accuracy. Rather than relying on aggressive or insult-based language, users should focus on providing clear, specific, and well-structured instructions. As LLM technology continues to evolve, understanding the relative importance of prompt content, prompt structure, and prompt tone will remain a critical area of research within prompt engineering and human-AI interaction studies.

V. CONCLUSION

This study investigated the impact of aggressive and insult-based prompting on the accuracy of Large Language Models (LLMs) through a comparative evaluation of ChatGPT, Gemini, and Claude. A total of 90 responses were collected from ten objective questions under three prompting conditions: Neutral, Aggressive, and Insult-Based. Response accuracy was evaluated using a binary scoring scheme, and statistical significance was assessed using the Chi-Square Test of Independence.

The experimental results show that prompt tone influences model performance differently across LLMs. ChatGPT achieved the highest overall accuracy of 90.00%, followed by Claude (80.00%) and Gemini (73.33%). Among the evaluated prompting strategies, Neutral prompting produced the highest average accuracy (86.67%), while Aggressive and Insult-Based prompting achieved average accuracies of 76.67% and 80.00%, respectively. Although some models exhibited performance variations under different prompting conditions, the statistical analysis revealed no significant relationship between prompt type and response accuracy ($\chi^2 = 1.015$, $p = 0.602$). Similarly, the differences in accuracy among the evaluated LLMs were not statistically significant ($\chi^2 = 2.756$, $p = 0.252$) at the 0.05 significance level. These findings suggest that aggressive or hostile language does not consistently improve LLM accuracy and may not be a reliable strategy for obtaining better responses. Instead, clear and concise instructions appear to remain the most effective interaction approach. The study contributes empirical evidence to a topic that is widely discussed within online AI communities but has received limited academic investigation.

Several limitations should be acknowledged. First, the experiment utilized a relatively small benchmark consisting of ten objective questions, which may limit the generalizability of the findings. Second, the evaluation focused solely on response accuracy and did not consider other important dimensions such as hallucination rate, reasoning quality, response consistency, or user satisfaction. Future work should expand the benchmark dataset to include a larger number of questions and more diverse task categories. Additionally, future studies may investigate the effects of prompt tone on other evaluation metrics, compare a broader range of LLMs, and explore whether aggressive prompting influences complex reasoning tasks differently from factual question-answering tasks. Such investigations would provide a deeper understanding of how linguistic style affects the behavior and reliability of modern AI systems.

REFERENCES

- [1] Naveed, H., Khan, A. U., Qiu, S., Saqib, M., Anwar, S., Usman, M., ... & Mian, A. (2025). A comprehensive overview of large language models. *ACM Transactions on Intelligent Systems and Technology*, 16(5), 1-72.
- [2] Sahoo, P., Singh, A. K., Saha, S., Jain, V., Mondal, S., & Chadha, A. (2024). A systematic survey of prompt engineering in large language models: Techniques and applications. *arXiv preprint arXiv:2402.07927*, 1.
- [3] Marvin, G., Hellen, N., Jjingo, D., & Nakatumba-Nabende, J. (2023, June). Prompt engineering in large language models. In *International conference on data intelligence and cognitive informatics* (pp. 387-402). Singapore: Springer Nature Singapore.
- [4] Foote, J., Kumar, D., Jha, B., Funkhouser, R., Bitsikokos, L., Goel, H., & Chiu, H. C. (2026). Taming Toxic Talk: Using chatbots to intervene with users posting toxic comments. *arXiv preprint arXiv:2601.20100*.
- [5] Anh-Hoang, D., Tran, V., & Nguyen, L. M. (2025). Survey and analysis of hallucinations in large language models: attribution to prompting strategies or model behavior. *Frontiers in Artificial Intelligence*, 8, 1622292.
- [6] Hassanein, F. E., Ahmed, Y., Maher, S., Barbary, A. E., & Abou-Bakr, A. (2025). Prompt-dependent performance of multimodal AI model in oral diagnosis: a comprehensive analysis of accuracy, narrative quality, calibration, and latency versus human experts. *Scientific Reports*, 15(1), 37932.
- [7] Zhang, S., Dong, L., Li, X., Zhang, S., Sun, X., Wang, S., ... & Wu, F. (2026). Instruction tuning for large language models: A survey. *ACM Computing Surveys*, 58(7), 1-36.
- [8] Choi, W. C., & Chang, C. I. (2025). A survey of techniques, key components, strategies, challenges, and student perspectives on prompt engineering for large language models (LLMs) in education.
- [9] Gozzi, M., & Fallucchi, F. (2026). Emotional Framing in Prompts Modulates Large Language Model Performance. *Big Data and Cognitive Computing*, 10(4), 102.
- [10] Myslinska, D. R. (2013). Contemporary first-generation European Americans: The unbearable whiteness of being. *Tul. L. Rev.*, 88, 559.
- [11] Santamaría-García, C. (2017). Emotional and educational consequences of (im) politeness in teacher-student interaction at higher education. *Corpus pragmatics*, 1(3), 233-255.
- [12] Liu, Y., Yao, Y., Ton, J. F., Zhang, X., Guo, R., Cheng, H., ... & Li, H. (2023). Trustworthy llms: a survey and guideline for evaluating large language models' alignment. *arXiv preprint arXiv:2308.05374*.
- [13] Cai, H., Shen, B., Jin, L., Hu, L., & Fan, X. (2025). Does tone change the answer? evaluating prompt politeness effects on modern llms: Gpt, gemini, llama. *arXiv preprint arXiv:2512.12812*.

Regression-Based Prediction and Performance Classification of Perovskite Solar Cell Efficiency

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ABSTRACT — Two-dimensional (2D) perovskite solar cells (PSCs) have attracted significant attention due to their improved environmental stability and tunable optoelectronic properties. However, optimizing their power conversion efficiency (PCE) remains challenging because device performance is influenced by complex interactions between material composition and fabrication parameters. In particular, the isolated influence of the A-site cation in 2D perovskites under fixed B-site and X-site conditions remains insufficiently explored using data-driven approaches. This study applies machine learning techniques to investigate the influence of A-site cation variation on the performance of 2D perovskite solar cells. A curated dataset compiled from peer-reviewed literature and reputable open-access materials databases was used, incorporating compositional features, selected electronic properties, and fabrication-related parameters. Exploratory data analysis (EDA) was conducted to examine data distributions, identify inconsistencies, and support feature selection. Instead of predicting continuous PCE values, the problem was formulated as a binary classification task by discretizing PCE into high- and low-performance classes based on the median value of the training data. The Random Forest model achieved the best overall classification performance with an accuracy of 80%.

KEYWORDS: A-site cation, perovskite solar cells, power conversion efficiency, Random Forest.

I. INTRODUCTION

In 2024, the global electricity demand increase by 4.3% due to the growing industrial activity, data centers expansion, artificial intelligence technologies and transportation sectors electrification [1]. Despite this growing demand, a large proportion of global electricity generation continues to rely on non-renewable energy sources such as coal and natural gas. This heavy dependence on fossil fuels has intensified concerns over environmental degradation, greenhouse gas emissions, and long-term energy sustainability.

In response to these challenges, renewable energy sources have gained increasing attention as viable alternatives. Among them, solar energy is regarded as one of the most promising options due to its wide availability, scalability, and low carbon footprint [2]. However, the widespread adoption of solar technology remains constrained by limitations associated with conventional silicon-based solar cells. These limitations include rigid material structures, complex installation requirements and high manufacturing costs [3]. Consequently, there is a pressing need to advance solar

technologies that offer improved efficiency, flexibility and cost-effectiveness to support the global transition toward sustainable energy systems.

2D perovskite materials are gaining interest for solar energy applications because of their enhanced stability and flexibility. However, these materials' PCE is still behind 3D perovskite performance. To improve the efficiency of 2D perovskites, it is important to understand how their chemical composition affects performance. Among the key components of the ABX_3 perovskite structure, the A-site ion significantly influences the material's structural integrity and electronic properties [4]. Nonetheless, systematically testing each potential A-site ion through experiments is impractical due to the vast number of possible candidates and synthesis challenges.

II. RELATED WORK

A. Machine Learning Model Selection

To address the challenges of multi-parameter optimization and limited data in PSC research, recent studies have increasingly turned to machine learning (ML) to uncover complex, non-linear relationships between composition, processing, and device performance. The choice of algorithm is pivotal, as different models offer distinct trade-offs in accuracy, interpretability, and data requirements. Random Forest (RF) is frequently employed for its robustness, inherent feature importance metrics, and strong performance on small-to-medium sized datasets, making it a reliable baseline for regression tasks like PCE prediction [5]. Gradient boosting methods like XGBoost often achieve higher predictive accuracy by iteratively correcting errors, and have been successfully used to model intricate phenomena such as recombination losses [6]. For classification tasks such as predicting stability categories or high/low-efficiency groups, Support Vector Machines (SVM) can be effective particularly in high-dimensional feature spaces [7]. Meanwhile, Artificial Neural Networks (ANNs) offer the greatest flexibility for modeling highly complex relationships but require larger datasets and offer less intrinsic interpretability, which can be a limitation for extracting scientific insight [8]. This trade-off between complexity and interpretability underscores the need for careful model selection, particularly for focused studies aiming to isolate specific effects, such as A-site cation engineering.

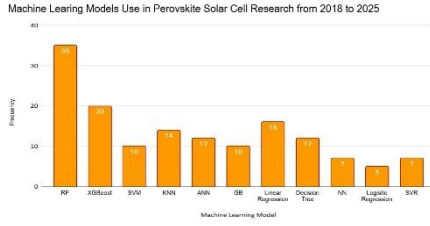


Figure 1. Machine Learning Use in PSCs Research.

B. Comparison of Studies Apply in PSCs

To illustrate the current landscape of ML applications in PSCs and the diversity of approaches, Table 1 summarizes key recent studies, comparing their objectives, dataset characteristics, and model performance.

Table 1. Comparison of Machine Learning Models Applied in PSCs

Author	Description	Dataset Size	Features	ML Models Used	Best ML Model
Ruman [9]	Predict PSCs performance metrics	26, 457 experimental data	29 features related to device architecture, film deposition and processing parameters.	RandomForestRegressor, XGBoost, GBR, DecisionTreeRegressor, SVR, BaggingRegressor, Ridge, KNeighborsRegressor, ExtraTreesRegressor, and CatBoostRegressor.	Random forest with R2 score 0.706.
Hussain [10]	Predict bandgap, PCE and device parameters	613 experimental data.	Material composition and stoichiometry, bandgap, device architecture, device stack layers and device area.	Random Forest (RF), Support Vector Regression (SVR), Artificial Neural Network (ANNs), Linear Regression	XGBoost with R2 score 0.88.
Gok [11]	Predict bandgap and PCE OF 2D PSCs	Eight different types of perovskite layers.	Composition, fabrication parameters, device architecture details and performance metrics.	Random Forest	Random forest with R2 average score 0.901.
Mammeri [5]	Predict PCE	300 experimental data	35 features related to electronic, manufacturing and environmental features.	Random Forest	Random forest with R2 score 0.864

III. METHODOLOGY

This research proposes a machine learning (ML)-based framework to predict and analyze the power conversion efficiency (PCE) of two-dimensional (2D) perovskite solar cells, with the aim of supporting data-driven performance optimization and reducing reliance on experimental trial-and-error approaches. Rather than directly optimizing device performance, the proposed approach focuses on identifying influential material, device, and processing parameters that govern PCE variability in 2D perovskite systems.

Machine learning has gained increasing attention in materials science due to its ability to capture complex, nonlinear relationships within high-dimensional experimental data[12]. In the context of perovskite solar cells, ML offers an effective alternative to purely empirical screening or computationally intensive first-principles methods by enabling rapid performance prediction and systematic feature analysis. When combined with physically motivated feature engineering and model interpretability techniques, ML can provide actionable insights that are relevant to experimental design [13].

The methodology adopted in this study addresses key limitations observed in prior ML-based perovskite research, particularly the insufficient treatment of feature interactions, limited interpretability of predictive models, and inconsistent evaluation strategies. To this end, a structured, multi-phase modelling pipeline is implemented which consist of baseline model development, model refinement through feature selection, and interaction-based feature engineering. Model performance is evaluated using both regression and classification perspectives, while interpretability is achieved through feature importance analysis and SHAP (SHapley Additive exPlanations). This framework enables a more transparent understanding of how material composition and fabrication conditions jointly influence PCE in 2D perovskite solar cells.

A. Research Design

This study employed a quantitative, data-driven research design based on supervised machine learning (ML) techniques to predict and analyze the power conversion efficiency (PCE) of two-dimensional (2D) perovskite solar cells. The research design was grounded in the premise that integrating experimentally reported parameters with data-driven modelling can reduce reliance on costly and time-consuming trial-and-error experimentation while providing systematic insight into performance-limiting factors in perovskite materials.

The overall workflow comprised data preprocessing, exploratory data analysis (EDA), feature selection, interaction-based feature engineering, model training, performance evaluation, and interpretability analysis. A multi-phase modelling strategy was adopted where its begin with baseline model development, followed by model refinement through feature reduction, and culminating in the incorporation of physically motivated interaction features. This structured approach ensured that the resulting models were not only predictive but also interpretable and scientifically meaningful.

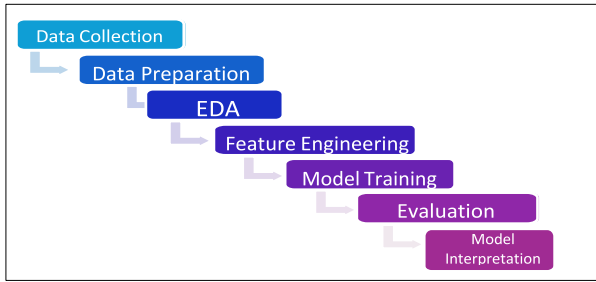


Figure 2. Research Design Flow.

B. Data Collection and Preprocessing

Data Sources

The dataset for this study was compiled from a combination of peer-reviewed publications and reputable open-access materials databases and a custom database from 2016 until 2025. The primary data sources included MaterialZone, scientific literature and other experimental studies which provide well-organized data on 2D perovskite compositions, manufacturing parameters, and device performance metrics. This curated dataset is suitable for machine learning applications which enable predicting modelling of power conversion efficiency and related performance characteristics.

In addition to this, further data was manually extracted from high-impact journal articles using literature mining tools to supplement the dataset with detailed compositional and performance records. The *NREL Best Research-Cell Efficiency Database* was consulted as a benchmark to validate reported power conversion efficiency (PCE) values to ensure the reliability and accuracy of the experimental data included in the study.

Data Description

The final dataset comprised 287 unique entries consisting of a structured set of independent variables and corresponding dependent variables relevant to the performance of 2D perovskite solar cells. The input features encompassed a chemical composition of A-site, electronic properties such as bandgap energy. Furthermore, fabrication-related data, such as annealing temperature, were included when available to account for process-dependent changes in device performance.

While the target variables included key performance metrics such as power conversion efficiency (PCE %) that was originally a continuous numerical feature representing the percentage efficiency of the solar cell. For classification tasks, the PCE values were applies a multi-class classification approach by categorising the performance into high, medium and low classed based on the median PCE of the training dataset. This data-driven threshold ensures balanced class representation and mitigates sensitivity to extreme values. These variables collectively reflect both compositional and process-dependent factors influencing device performance.

Data Cleaning

The raw dataset was first filtered to retain only samples with fixed B-site (Pb) and X-site (I) ions, allowing the study to isolate the influence of A-site variation on device performance. Suspicious or clearly erroneous rows were manually removed, and unnecessary metadata columns (e.g., DOI, author, publication date) were dropped.

Numeric columns such as Perovskite Thickness (nm), Fabrication Temperature (°C) and PCE (%) were cleaned by removing non-numeric characters and converting the values to numeric types. Entries with missing PCE values were excluded, as these represent the target variable for supervised learning. For categorical columns such as A Cation, ETL, HTL, Substrate, and Solvent, missing values were filled with a placeholder “Missing” and whitespace was removed.

To encode categorical variables for machine learning models, target encoding was applied. This technique replaces each category with a smoothed average of the target variable (PCE) corresponding to that category, providing a numeric representation while preserving the relationship between the feature and the target. Less frequent categories were implicitly downweighed through the smoothing factor to avoid overfitting.

Exploratory Data Analysis (EDA)

EDA were used to uncover underlying trends in the compositional, structural, and electronic features of 2D perovskite solar cells and their association with performance metrics such as power conversion efficiency (PCE). This step is essential not only for gaining domain insights but also for guiding subsequent processes such as feature selection, data transformation, and model choice.

A variety of visualization techniques and statistical summaries were employed in this research. First, histograms and bar plot were used to examine the distribution of continuous variables such as bandgap energy, PCE and others fabrication features. This technique helps in identifying skewness, modality, and potential outliers. Next, boxplots were used to compare these distributions boxplots will help compare these distributions across categorical variables like A-site ion, B-site ion and X-halide type. While scatter plots were particularly valuable for assessing potential nonlinear relationships between pairs of variables such as between bandgap and PCE. Additionally, pair plots are used to observe multi-feature interactions in a compact format.

To investigate inter-feature relationships, correlation heatmaps were generated using Pearson or Spearman coefficients depending on data normality. These heatmaps highlighted the degree of linear correlation among numerical features and between features and key target variables like PCE. Identifying strongly correlated input features helps to reduce multicollinearity, particularly in regression-based models. Furthermore, grouped bar plots were utilized to investigate how categorical factors affect mean or distributional shifts in the target variables.

Through EDA, this study aims to answer several key research questions of which material or device features show the strongest statistical association with PCE, the clear differences in performance based on composition groups and the optimal range of features such as bandgap for high-performing 2D perovskites. Insights from this analysis will inform both feature selection and modelling strategy.

Feature Importance

Feature selection are pivotal steps in developing robust and interpretable machine learning models for predicting the performance of 2D perovskite solar cells. This process involves selecting the most relevant features to improve model accuracy while minimizing overfitting and computational complexity.

Feature Engineering

Feature engineering was performed to improve model performance and interpretability by transforming, encoding, and creating relevant features from the curated dataset. Categorical features such as A-site cation, ETL, HTL, solvent, and substrate were encoded numerically using target encoding to preserve predictive information while maintaining model efficiency.

In addition, interaction terms between key features were generated to capture possible combinatorial effects on PCE. For example, interactions between A-site cation and ETL, as well as thickness and fabrication temperature, were computed to enable the model to learn potential synergistic effects between composition and processing parameters. Continuous features such as bandgap, perovskite thickness, and fabrication temperature were kept as numeric values, while missing values were handled using group-wise median imputation or model-based prediction to maintain data completeness.

Feature Selection

Selecting the most informative features is critical to reduce dimensionality, avoid multicollinearity, and improve generalization. This study initially applied correlation analysis to help identify redundant features with high intercorrelation and remove the variables that contribute little unique information.

Machine Learning Model Development

This study employed a comparative machine learning approach, evaluating six supervised models: Random Forest (RF), Extreme Gradient Boosting (XGBoost), Support Vector Regression (SVR), CatBoost, Gradient Boosted Regression Trees (GBRT), and AdaBoost. These models were selected based on their frequent and successful application in perovskite solar cell (PSC) research and their ability to handle high-dimensional, structured scientific data.

Random Forest was chosen as the primary model for interpretability due to its robustness, ability to handle mixed data types, and built-in feature importance measures. Conceptually, it is an ensemble method that constructs multiple decision trees and outputs the average prediction which effectively reducing overfitting through bootstrap aggregation. XGBoost, CatBoost, and GBRT were included for their gradient-boosting frameworks, which iteratively correct errors in previous trees and provide enhanced accuracy and regularization. SVR and AdaBoost were included to capture complementary perspectives, with SVR being suitable for modelling nonlinear relationships in small to medium datasets and AdaBoost providing adaptive weighting of samples to improve weak learners.

All models were trained and tested on an 80:20 stratified train-test split to maintain the distribution of high- and low-PCE classes. To ensure robustness and generalizability, 5-fold cross-validation was applied on the training set. Hyperparameter tuning was performed using Grid Search Cross-Validation, exploring key parameters specific to each model (e.g., number of trees and max depth for RF, learning rate and estimator number for XGBoost, regularization parameters for SVR). This multi-model approach enabled a thorough comparison of predictive performance, while emphasizing interpretability and actionable insights through Random Forest feature analysis.

The selection of these models was also informed by prior literature. For example, Random Forest has been successfully used by [9] to predict PSC performance using over 42,000 experimental datapoints, while XGBoost achieved the highest R^2 in predictive studies of PCE [10]. CatBoost and GBRT are widely recognized for handling categorical features efficiently, and SVR and AdaBoost have been shown to provide complementary performance in regression tasks with complex feature interactions.

Model Evaluation and Interpretation

After training and validation, the models were evaluated using both regression and classification metrics to provide a comprehensive assessment. For regression, the continuous PCE predictions were assessed using Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and R^2 to capturing both prediction accuracy and variance explained.

For classification, the continuous PCE values were discretized into high, medium, and low classes using a threshold derived from the training set. Classification performance was evaluated using accuracy, precision, recall, F1-score, and the confusion matrix to provide a holistic view of model performance. In addition, the Receiver Operating Characteristic-Area Under the Curve (ROC-AUC) score was calculated using a one-vs-rest (OvR) strategy to assess the model's ability to distinguish each PCE class against the others. Both macro-averaged and weighted-average AUC scores were reported to account for potential class imbalance.

To ensure robustness and mitigate the effects of data distribution bias, stratified k-fold cross-validation was employed during model validation, preserving the distribution of high, medium, and low PCE categories across folds.

Furthermore, SHAP (SHapley Additive exPlanations) analysis was performed to interpret the contribution of each feature to model predictions, providing insight into how material composition, device architecture, and processing parameters influence both continuous PCE values and classified PCE categories. This interpretability is particularly valuable for tree-based models such as Random Forest and gradient boosting algorithms.

Other evaluation metrics, such as Matthews Correlation Coefficient (MCC) or Cohen's Kappa, could be incorporated in future studies to further assess classification performance in the presence of significant class imbalance. The final model was selected based on a balance between regression accuracy, classification performance, interpretability, and generalizability across different 2D perovskite compositions.

IV. RESULT AND ANALYSIS

The results presented the predictive performance of the Random Forest model and highlighted how features such as A-Cation identity, ETL combinations, bandgap, and solvent vary across High and Low PCE classes. In this discussion, these findings are interpreted to understand the underlying factors affecting power conversion efficiency in 2D perovskites. In particular, the discussion explores the effects of the A-site cation, feature interactions, model performance, and feature importance, while also considering the practical implications, limitations, and future research directions of this study.

The cleaned dataset consisted of 178 samples of 2D perovskite solar cells with a fixed B-site metal of lead (Pb), a fixed X-site halide of iodine (I) and 50 unique A-site cations. Following data preprocessing, eight fabrication-related features were used as input features for machine learning model development such as bandgap (eV), perovskite thickness (nm), relative humidity (%), fabrication temperature ($^{\circ}\text{C}$), electron transport layer (ETL), hole transport layer (HTL), substrate and solvent.

The PCE of the 178 samples ranged from 0.22% to 34% with a mean of 13.26% and standard deviation of 5.09%. As shown in Figure 3, the majority of samples exhibited PCE values between approximately 8% to 15.5%. This distribution indicates moderate variability with a slight skewness toward higher efficiency values.

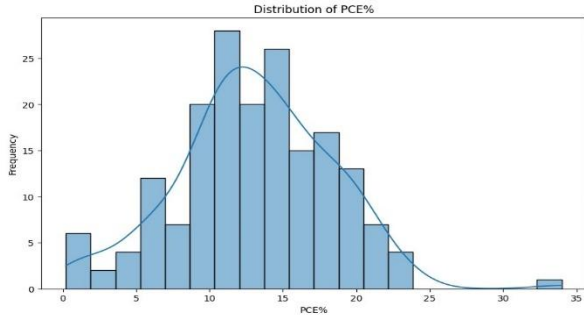


Figure 3. PCE% Distribution.

Figure 4 shows the distribution of A-site cations in the dataset. The dataset contains 50 unique A-site ions, with a highly imbalanced distribution where several ions appear only once or twice, while a small number of ions dominate the dataset. This imbalance reflects the experimental nature of available perovskite data and highlights the challenges in developing machine learning models that generalize well across different A-site compositions.

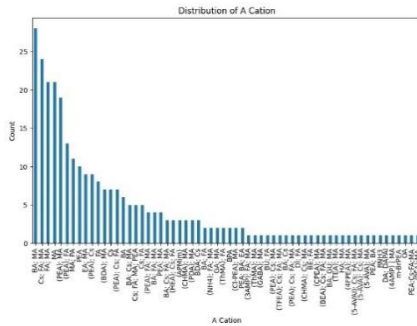


Figure 4. A-site Cation Distribution.

Figure 5 illustrates the distribution of PCE values across different A-site ions. Several A-site ions such as FA exhibit a wide range of PCE values rather than a single consistent performance level. This indicates that the efficiency of 2D perovskite solar cells is not solely determined by the choice of A-site ion but is also influenced by other factors such as fabrication conditions. The observed variability highlights the presence of complex and nonlinear interactions between composition and processing parameters.

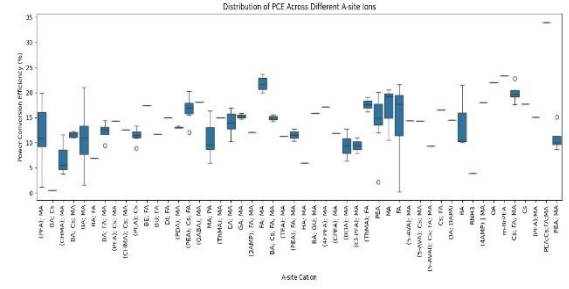


Figure 5. PCE Distribution Across Different A-Cation.

Figure 6 and 7 illustrates the distribution of PCE across different B-site metals and X-site halides in the dataset. Pb-based perovskites exhibit a wider distribution of higher PCE values compared to other B-site metals, while iodine-based halides show superior performance relative to bromide and chloride. Based on this observation and to reduce chemical variability, Pb and I were selected as fixed components for subsequent machine learning analysis which then allowing focused investigation of A-site ion effects and fabrication-related parameters.

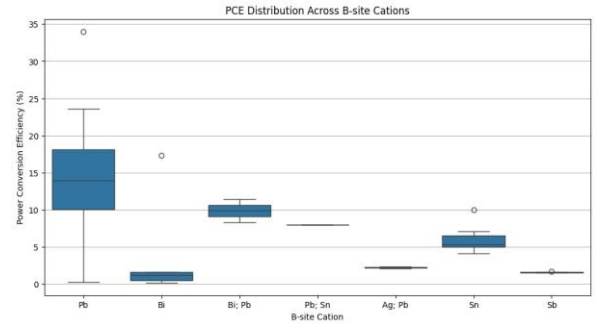


Figure 6. PCE Distribution Across Different B-site Cations.

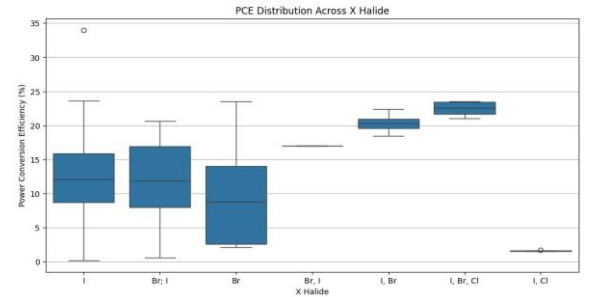


Figure 7. PCE Distribution Across Different X-site Halides.

A. Correlation of Fabrication Features with Performance

The correlation heatmap (Figure 8) illustrates the linear relationships between PCE and fabrication-related features. Among all variables, the A-site cation exhibits the strongest positive correlation with PCE ($r = 0.60$), followed by electron transport layer (ETL) ($r = 0.57$), hole transport layer (HTL) ($r = 0.51$), substrate ($r = 0.47$), and solvent ($r = 0.47$). These results indicate that material selection-related features show stronger linear associations with device performance compared to process parameters.

In contrast, perovskite thickness ($r = 0.14$), relative humidity ($r = 0.13$), fabrication temperature ($r = 0.07$), and bandgap ($r = 0.07$) exhibit weak correlations with PCE which suggests limited direct linear influence when considered independently.

Additionally, moderate to strong correlations are observed among several fabrication related features. Notably, ETL shows strong correlations with HTL ($r = 0.60$), A-site cation ($r = 0.57$), and substrate ($r = 0.56$). Similarly, HTL is moderately correlated with substrate ($r = 0.54$), solvent ($r = 0.36$), and bandgap ($r = 0.37$). These inter-feature correlations indicate that certain material and fabrication choices tend to occur together within the dataset.

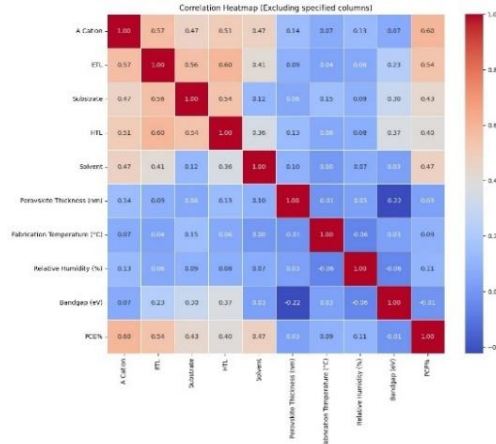


Figure 8. Correlation Heatmap.

B. Machine Learning Model Performance

Table 2 presents the regression performance of six machine learning models in predicting the power conversion efficiency (PCE) of 2D perovskite solar cells. The models were evaluated using RMSE, MAE, and R^2 on the test dataset. Among all models, XGBoost achieved the lowest RMSE (3.84) and highest R^2 (0.40), followed closely by Random Forest, which recorded an RMSE of 3.94 and an R^2 of 0.37.

The SVR model achieved a comparable MAE of 2.73 but exhibited a slightly lower R^2 value of 0.35. CatBoost showed similar predictive performance with an RMSE of 3.97 and an R^2 of 0.36. In contrast, GBRT and AdaBoost produced higher RMSE values exceeding 4.0 and lower R^2 scores, indicating reduced predictive accuracy relative to the other models.

Overall, the results demonstrate noticeable performance differences among the evaluated models in predicting PCE for 2D perovskite solar cells.

Table 1 Baseline Model Result

Model Performance	RMSE	MAE	R2
Random Forest	3.9369	2.7594	0.3712
XGBoost	3.8400	2.7547	0.4017
SVR	3.9882	2.7251	0.3547
CatBoost	3.9697	2.8318	0.3607

GBRT	4.4104	3.2132	0.2108
AdaBoost	4.0443	2.9916	0.3364

C. Model Performance After Feature Selection

After dropping the HTL, Substrate, and Relative Humidity features, the remaining four models were evaluated on the test set. CatBoost achieved the lowest RMSE of 3.732 and the lowest MAE of 2.518, indicating the smallest average prediction error among the models. Random Forest followed with an RMSE of 3.809 and an MAE of 2.647, while SVR and XGBoost achieved RMSE values of 3.949 and 4.008, and MAE values of 2.765 and 2.792, respectively.

In terms of variance explained (R^2), CatBoost and XGBoost performed best, with values of 0.4350 and 0.4348, whereas Random Forest and SVR achieved 0.4114 and 0.3672. Based on the combined evaluation of RMSE, MAE, and R^2 , CatBoost and Random Forest demonstrated the most favorable performance and were therefore selected for subsequent feature engineering and interpretability analyzes.

Table 2 Model Refinement Result

Model Performance	RMSE	MAE	R2
Random Forest	3.8090	2.6470	0.4114
XGBoost	4.0080	2.7915	0.3482
SVR	3.9494	2.7651	0.3672
CatBoost	3.7319	2.5185	0.4350

D. Model Performance After Feature Engineering

The performance of the selected machine learning models which are Random Forest and CatBoost was evaluated on the test dataset after applying feature engineering by including interaction features. Random Forest model achieved a Root Mean Squared Error (RMSE) of 3.6594, a Mean Absolute Error (MAE) of 2.5383, and an R^2 of 0.4567. The CatBoost model demonstrated an RMSE of 3.7275, an MAE of 2.6362, and an R^2 of 0.4363.

The results indicate that both models maintained comparable predictive performance after feature engineering with Random Forest showing slightly lower error values and a marginally higher R^2 which are presented in Table IV.

Table 3 Model with Feature Engineering Result

Model Performance	RMSE	MAE	R2
Random Forest	3.6594	2.5383	0.4567
CatBoost	3.7275	2.6362	0.4363

E. Classification of Predicted PCE from Final Regression Model

The classification performance of the final regression models was evaluated by converting the predicted PCE values into High and Low performance classes using the median PCE of the training set as the threshold. Table 5 summarizes the classification results in terms of accuracy, macro-averaged precision, recall, and F1-score.

The Random Forest model achieved an accuracy of 0.80, with a macro precision of 0.79, macro recall of 0.81, and macro F1-score of 0.79, indicating balanced classification performance across both classes. In comparison, the CatBoost model obtained an accuracy of 0.72, with macro precision, recall, and F1-score values of 0.67, 0.72, and 0.71, respectively.

Overall, Random Forest demonstrated stronger and more consistent classification performance than CatBoost when applied to the predicted PCE values.

Table 4 Classification Model Result Using Predicted PCE From Final Regression Model

Model Performance	Accuracy	Macro Precision	Macro Recall	Macro F1Score
Random Forest	0.80	0.79	0.81	0.79
CatBoost	0.72	0.671	0.72	0.71

F. Feature Importance

Table 6 presents the feature importance scores obtained from the final selected Random Forest regression model. The results indicate that the interaction between A-site cation and electron transport layer (ACation_ETL_interaction) is the most influential feature, contributing approximately 29.6% of the total importance. This is followed by the electron transport layer (ETL) alone, with an importance score of 21.8%.

Among the remaining features, bandgap (13.7%) and A-site cation (9.6%) show notable contributions to the prediction of PCE. Fabrication temperature (8.6%) and the interaction between perovskite thickness and fabrication temperature (7.0%) exhibit moderate importance. In contrast, perovskite thickness (5.1%) and solvent (4.6%) contribute relatively less to the model predictions.

Overall, the feature importance results suggest that both material-related factors and interaction effects between composition and fabrication conditions play a substantial role in determining PCE in 2D perovskite solar cells.

Table 5 Feature Importance Result of Random Forest

Feature	Importance
ACation ETL interaction	0.295803
ETL	0.218055
Bandgap (eV)	0.137084
A Cation	0.096361
Fabrication Temperature (C)	0.085692
Thickness Temp interaction	0.070083
Perovskite Thickness (nm)	0.050957
Solvent	0.045965

G. SHAP Analysis

Figure 9 presents the SHAP summary plot for the Random Forest regression model, illustrating the relative contribution of each input feature to the predicted PCE. The features are ranked in descending order based on their mean absolute SHAP values.

The interaction between A-site cation and electron transport layer (ACation_ETL_interaction) exhibits the highest overall impact on model output, followed by ETL and A-site cation. These features show a wide spread of SHAP values which indicates strong influence on both high and low PCE predictions.

Bandgap also contributes noticeably to the model predictions, with both positive and negative SHAP values observed across samples. Solvent and perovskite thickness demonstrate moderate influence, while fabrication temperature and the thickness–temperature interaction exhibit comparatively smaller SHAP magnitudes which suggests a lower contribution to prediction variability.

Overall, the SHAP results confirm that interaction-based features and transport-layer-related parameters play a dominant role in the Random Forest model's prediction of PCE.

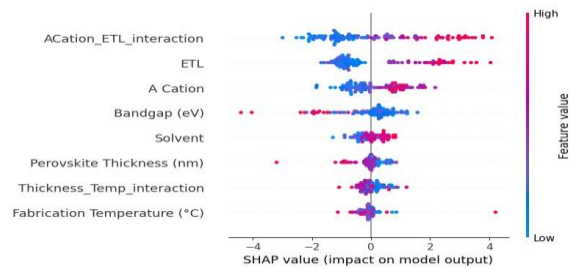


Figure 9. Random Forest SHAP Analysis.

H. Predictive Analysis

Table 7 shows a comparison of key features for samples with the same A-Cation ((PEA):MA) that were classified as High or Low PCE by the Random Forest model. For the High PCE class, the ETL is predominantly TiO₂-c, the Bandgap ranges from 1.67 eV, and the Solvent used is DMF. In contrast, for the Low PCE class, the ETL is PCBM-60 or PCBM-60|LiF, the Bandgap ranges from 1.60–1.64 eV, and the Solvent is either DMF or Methylammonium acetate.

This table illustrates that even for the same A-Cation, variations in other fabrication and material features are associated with different predicted PCE classes.

Table 6 Correct Predictions of Random Forest Model

A Cation	High Class					
	ETL		Bandgap		Solvent	
	Min	Max	Min	Max	Min	Max
(PEA):M A	TiO ₂ -c	TiO ₂ -c	1.67	1.67	DM F	DM F

A Cation	Low Class					
	ETL		Bandgap		Solvent	
	Min	Max	Min	Max	Min	Max
(PEA):M A	PCB M- 60	PCB M- 60 Li F	1.60	1.64	DMF	Meth ylam moni um aceta te

V. CONCLUSION

This study investigated the application of machine learning techniques to predict and analyze the power conversion efficiency of 2D perovskite solar cells, with a particular focus on isolating the effects of the A-site cation and its interaction with device and processing parameters. By integrating exploratory data analysis, model refinement, feature engineering, and interpretability analysis, this work aimed to improve both predictive performance and physical understanding of efficiency-driving factors in 2D perovskite systems.

Among the evaluated models, Random Forest consistently demonstrated robust performance and was selected as the final predictive model. Progressive refinement through feature selection and interaction-based feature engineering led to notable improvements in predictive accuracy, with interaction features especially the A-cation and ETL interaction that emerging as dominant contributors to model output. The results further revealed that device architecture and processing conditions, including ETL choice, bandgap, solvent, and perovskite thickness, play a critical role in explaining why identical A-site cations can exhibit substantially different PCE values.

Overall, the findings highlight that optimizing 2D perovskite solar cell performance requires a holistic consideration of material selection and processing conditions rather than isolated parameter tuning. While the proposed framework is constrained by data availability and experimental variability, it offers a transparent and extensible foundation for future data-driven optimization and experimental validation of high-efficiency 2D perovskite solar cells.

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REFERENCES

- [1] International Energy Agency "Growth in global energy demand surged in 2024 to almost twice its recent average." https://www.iea.org/news/growth-in-global-energy-demand-surged-in-2024-to-almost-twice-its-recent-average?utm_source (accessed).
- [2] K. Sonkar, A. Pandey, and A. K. Verma, "Potential, recent status and future scope of solar energy," *J. Ravishankar Univ.*, vol. 37, no. 2, pp. 30-38, 2024/12/29 2024, doi: 10.52228/jrub.2024-37-2-4.

- [3] M. Di Sabatino, R. Hendawi, and A. S. Garcia, "Silicon Solar Cells: Trends, Manufacturing Challenges, and AI Perspectives," *Crystals*, vol. 14, no. 2, p. 167, 2024, doi: 10.3390/cryst14020167.
- [4] S. Ramos-Terrón *et al.*, "A-site cation engineering and halide tuning precursor engineering to tune the optical properties of 2D perovskites," *RSC Advances*, vol. 15, no. 34, pp. 28181-28190, 2025, doi: 10.1039/d5ra03422a.
- [5] M. Mammeri *et al.*, "Targeting high performance of perovskite solar cells by combining electronic, manufacturing and environmental features in machine learning techniques," *Heliyon*, vol. 9, no. 11, p. e21498, 2023, doi: 10.1016/j.heliyon.2023.e21498.
- [6] B. Akbar, H. Tayara, and K. T. Chong, "Unveiling dominant recombination loss in perovskite solar cells with a XGBoost-based machine learning approach," *iScience*, vol. 27, no. 3, 2024, doi: 10.1016/j.isci.2024.109200.
- [7] J. S. Pimentel, R. Ospina, and A. Ara, "A novel fusion Support Vector Machine integrating weak and sphere models for classification challenges with massive data," *Decision Analytics Journal*, vol. 11, p. 100457, 2024/06/01/ 2024, doi: <https://doi.org/10.1016/j.dajour.2024.100457>.
- [8] M. N. Kumar, "Artificial Neural Networks and its Applications: A Review," *International Journal of Advance Research and Innovation*, vol. Vol. 8(2), 2020, doi: 10.51976/ijari.822003.
- [9] A. H. Rumman *et al.*, "Data-driven design for enhanced efficiency of Sn-based perovskite solar cells using machine learning," *APL Machine Learning*, vol. 1, no. 4, 2023, doi: 10.1063/5.0177271.
- [10] W. Hussain, S. Sawar, and M. Sultan, "Leveraging machine learning to consolidate the diversity in experimental results of perovskite solar cells," *RSC Adv*, vol. 13, no. 32, pp. 22529-22537, Jul 19 2023, doi: 10.1039/d3ra02305b.
- [11] E. C. Gok *et al.*, "Predicting Perovskite Bandgap and Solar Cell Performance with Machine Learning," *Solar RRL*, vol. 6, no. 2, p. 2100927, 2022, doi: <https://doi.org/10.1002/solr.202100927>.
- [12] P. Karande, B. Gallagher, and T. Han, "A Strategic Approach to Machine Learning for Material Science: How to Tackle Real-World Challenges and Avoid Pitfalls," *Chemistry of Materials*, vol. 34, 09/01 2022, doi: 10.1021/acs.chemmater.2c01333.
- [13] Q. Tao, P. Xu, M. Li, and W. Lu, "Machine learning for perovskite materials design and discovery," *npj Computational Materials*, vol. 7, no. 1, 2021, doi: 10.1038/s41524-021-00495-8.

Human-in-the-Loop Agentic AI Workflow Architecture for Smart Campus Administrative Automation

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ABSTRACT — Administrative workflow management in higher education institutions continues to rely on deterministic document routing and manual approval coordination, resulting in bottlenecks, routing inconsistencies, and limited traceability. While Agentic AI offers new capabilities for intelligent document orchestration, fully autonomous AI decision-making introduces governance and accountability risks in institutional settings. This paper proposes a Human-in-the-Loop (HITL) Agentic AI Workflow Architecture for smart campus administrative automation. The proposed architecture operationalizes HITL as a structured institutional control mechanism that specifies explicit decision checkpoints, role-based authority boundaries, and escalation conditions, embedded within a seven-agent AI orchestration framework. The study adopts a Design Science Research (DSR) methodology, and the architecture is evaluated through scenario-based feasibility validation with explicit pass/fail criteria across five representative administrative workflow scenarios. Validation results confirm that the proposed architecture supports adaptive document routing and governance-consistent workflow execution while preserving institutional accountability and decision legitimacy.

KEYWORDS: Agentic AI; Human-in-the-Loop; workflow orchestration; smart campus; administrative automation; governance-aware AI; document routing; auditability.

I. INTRODUCTION

Digital transformation in higher education has progressed from basic document digitization toward workflow automation, service orchestration, and governance transparency enhancement [1], [2], [20]. Smart campus initiatives now integrate information technology, data analytics, and artificial intelligence to support both academic and administrative operations in an adaptive, interconnected manner [3], [4]. Within this context, administrative document management, which encompasses disposition, routing, approval, and institutional correspondence, represents a critical yet under automated operational domain.

Despite widespread adoption of e-office platforms and workflow systems, most university administrative processes continue to rely on manual disposition procedures, deterministic routing rules, and multi-level approval mechanisms that introduce bottlenecks, routing inconsistencies, and limited traceability [5], [6]. Existing systems function as document distribution platforms lacking capability to interpret context or generate context-aware routing recommendations [7].

Higher education administrative environments in developing countries present distinctive governance challenges. Indonesian universities operate under multi-level institutional hierarchies that span departmental, faculty, and rectorate authorities, subject to regulatory compliance requirements (e.g., BAN-PT accreditation standards) that impose strict documentation and approval audit requirements. Simultaneous management of academic, financial, legal, and operational document streams creates routing complexity that generic workflow systems cannot adequately address.

Recent studies confirm that AI-powered workflow automation in higher education can reduce manual administrative processing time by up to 62% while improving document processing accuracy, yet effective deployment requires integrated governance mechanisms to address data privacy, algorithmic accountability, and regulatory compliance requirements [16]. This evidence reinforces the need for an architecture that combines intelligent automation with structured human oversight.

Recent advances in Large Language Models (LLMs) and Agentic AI have created new opportunities for adaptive, context-aware administrative orchestration [8], [9]. Agentic AI systems can perform document understanding, task planning, tool utilization, and multi-step workflow coordination semi-autonomously [8]. However, unrestricted AI autonomy introduces governance, transparency, and accountability risks [10], [11]. Autonomous routing decisions may contravene institutional authority structures and undermine the legitimacy of administrative processes [12].

Human-in-the-Loop (HITL) mechanisms have been widely recognized as essential for maintaining human decision authority in AI-assisted institutional processes [13]. However, existing literature addresses HITL predominantly as a conceptual governance principle rather than an operationalized architectural component. There remains a gap in architectures that structurally embed HITL as a role-aware institutional control mechanism within Agentic AI workflow orchestration.

To address this gap, this paper proposes a Human-in-the-Loop Agentic AI Workflow Architecture for Smart Campus Administrative Automation, guided by three research questions:

RQ1: How can Agentic AI orchestration be integrated with structured HITL governance to support adaptive administrative document routing in smart campus environments?

RQ2: What architectural components and governance rules are required to ensure institutional accountability and workflow traceability in AI-assisted workflows?

RQ3: How does the proposed architecture perform across diverse administrative scenarios in terms of routing feasibility, governance consistency, and auditability?

The primary contributions are: (1) a governance-aware Agentic AI workflow architecture operationalizing HITL through explicit decision checkpoints, role-based authority boundaries, and escalation conditions; (2) a seven-agent orchestration model integrating semantic document understanding, routing recommendation, priority assessment, and audit logging; and (3) a scenario-based DSR feasibility evaluation with explicit pass/fail criteria across representative smart campus administrative scenarios.

II. RELATED WORK

A. Smart Campus and Digital Governance

Smart campus frameworks integrate digital infrastructure, academic services, and administrative systems to support institutional efficiency and governance [3], [4]. Jurva *et al.* [7] identify administrative orchestration as a foundational component of smart campus digital infrastructure. Studies on digital governance emphasize accountability, transparency, and coordination mechanisms as prerequisites for effective digital transformation [1], [6]. However, most smart campus research concentrates on IoT infrastructure and learning environments, with limited attention to AI-assisted administrative workflow orchestration.

In the Indonesian higher education context, governance complexity is further amplified by BAN-PT accreditation requirements, which mandate systematic documentation of institutional processes, traceability of administrative decisions, and audit-ready records across all operational units [17]. Pratiwi and Kusumah [17] demonstrate that Indonesian universities face significant institutional challenges in maintaining autonomy, transparency, and accountability simultaneously, which are precisely the conditions under which governance-aware AI orchestration offers the greatest operational value.

B. Workflow Automation and Document Routing

Soares and Calejo [5] demonstrate that intelligent document routing constitutes a foundational step toward workflow automation. Samiri *et al.* [14] extend this through adaptive workflow management using learning models. Despite these advances, existing routing approaches rely on rule-based classification without semantic document understanding. Workflow automation research has not addressed human validation, escalation mechanisms, or auditability as core architectural components. This gap is particularly consequential in campus administration, where routing decisions require institutional authorization.

C. Agentic AI and Workflow Orchestration

Agentic AI extends intelligent systems toward agents capable of context understanding, action planning, tool utilization, and multi-step coordination [8], [9]. Bandi *et al.* [8] identify orchestration, persistent memory, and tool-use as defining Agentic AI capabilities. Marrella [10] demonstrates automated planning for business process management. However, Agentic AI research focuses predominantly on enterprise automation, with the application to institutional workflows where governance boundaries and authority hierarchies are operationally significant, an area that remains underexplored.

A fundamental distinction between existing Agentic AI architectures and the requirements of institutional administrative workflows lies in the treatment of authority boundaries. General-purpose Agentic AI systems [8], [9] are designed to maximize autonomous task completion, with human intervention treated as an exception. In contrast, higher education administrative workflows require that human authority is the norm, specifically for documents carrying financial, legal, or strategic implications. This inversion of the autonomy assumption represents a foundational design requirement that existing Agentic AI frameworks have not addressed, motivating the governance-embedded architecture proposed in this study.

D. Human-in-the-Loop Governance

HITL mechanisms preserve human decision authority over AI outputs in high-stakes processes [13]. Mosqueira-Rey *et al.* [11] survey HITL approaches in machine learning, while McKay *et al.* [13] address AI governance with human oversight in organizational contexts. Barsekh-Onji *et al.* [12] examine governance implications of AI in public administration. A critical limitation is that HITL is treated as a design aspiration rather than a specified operational mechanism with defined approval hierarchies, escalation conditions, and audit trail structures.

E. Research Gap

Table I summarizes the state of the art. No existing work integrates all five dimensions, namely smart campus context, workflow automation, intelligent document routing, Agentic AI orchestration, and operationalized HITL governance, within a unified architecture. Note: SC=Smart Campus, WA=Workflow Automation, DR=Document Routing, P=Partial.

Table 1 State-of-the-Art Comparison

Study	SC	WA	DR	AI	HITL	Audit
Soares & Calejo [5]	X	✓	✓	X	X	X
Samiri <i>et al.</i> [14]	X	✓	P	P	X	X
Marrella [10]	X	✓	P	✓	X	X
Mosqueira-Rey [11]	X	X	X	P	✓	P
McKay <i>et al.</i> [13]	X	X	X	P	✓	✓
Bandi <i>et al.</i> [8]	X	P	X	✓	P	P
This Work	✓	✓	✓	✓	✓	✓

III. RESEARCH METHODOLOGY

A. Design Science Research Approach

This research adopts the Design Science Research (DSR) methodology following Peffers *et al.* [15], which structures research into six activities: (1) problem identification, (2) solution objectives definition, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. DSR is appropriate because the objective is to construct an architectural artifact addressing a practical problem while contributing to scientific knowledge on governance-aware AI orchestration.

The artifact is the proposed architecture, evaluated through scenario-based feasibility validation consistent with DSR evaluation guidelines for architectural artifacts [15]. This approach demonstrates feasibility through structured scenario analysis prior to production implementation [11], [13], [15].

Hevner *et al.* [18] further establish that DSR artifacts, including architectural models, are appropriately evaluated through demonstration and structured assessment of their utility within a defined problem context, without requiring full production deployment as a prerequisite for research validity. This principle underpins the scenario-based feasibility validation approach adopted in this study, positioning the architectural artifact as the primary research contribution subject to systematic evaluation.

B. Research Stages

The research proceeds through four DSR-aligned stages: (1) Problem Identification, which involved analysis of workflow inefficiencies, routing inconsistencies, and governance gaps in higher education institutions; (2) Architecture Design, covering development of the seven-layer HITL Agentic AI architecture with specified agent roles, governance rules, and audit mechanisms; (3) Workflow Modeling, defining end-to-end orchestration flow definition; and (4) Scenario-Based Evaluation, involving feasibility validation across five administrative scenarios using four explicitly defined dimensions.

The Problem Identification stage was grounded in analysis of administrative document management practices at Indonesian universities, identifying recurring inefficiencies: disposition bottlenecks caused by absent approvers, routing errors due to unclear document classification, and limited audit trail availability for post-hoc governance review [16]. These observations established the functional requirements driving the

architectural design. The Architecture Design stage translated these requirements into a seven-layer specification with governance integration as a primary design constraint, ensuring that HITL enforcement is architecturally mandatory rather than optionally configurable [18]. The Workflow Modeling stage defined the complete orchestration sequence, including inter-agent data transfer protocols, governance validation triggers, and escalation state transitions. The Scenario-Based Evaluation stage operationalized these specifications into five traceable administrative workflow scenarios with explicit pass/fail criteria, consistent with DSR evaluation guidelines for conceptual architectural artifacts [15], [18].

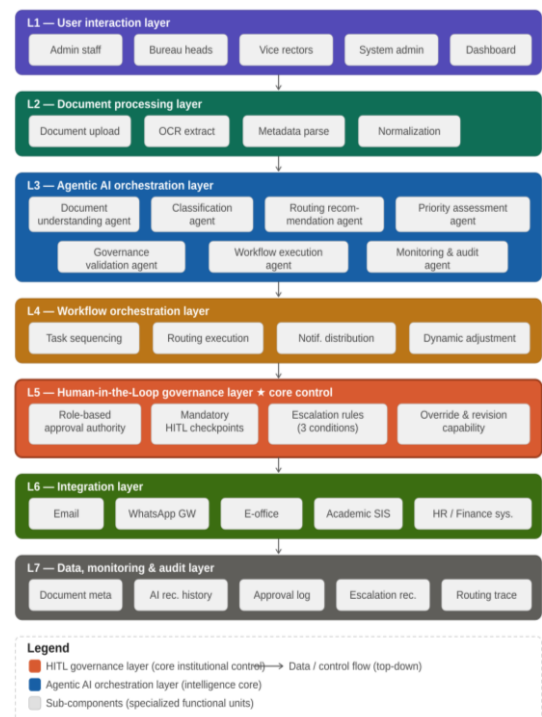
C. Scenario-Based Feasibility Validation

Five scenarios represent document diversity, authority levels, and governance requirements: S1 (Tier 1): incoming administrative letter; S2 (Tier 2): academic document with multi-level review; S3 (Tier 3): financial proposal requiring mandatory HITL; S4 (Tier 3): cooperation request requiring legal/executive review; S5 (Tier 4): ambiguous document triggering AI confidence-based escalation. Each scenario is traced end-to-end and assessed against four dimensions with explicit pass/fail criteria defined in Table II.

IV. PROPOSED ARCHITECTURE

A. Architecture Overview

The proposed architecture is a seven-layer, governance-aware orchestration framework for smart campus administrative document routing. Its defining characteristic is that institutional governance control is embedded structurally within the AI orchestration process as a co-equal architectural layer, rather than applied as an external oversight mechanism. This directly addresses the HITL operationalization gap identified in Section II. Figure 1 illustrates the overall architecture.

**Figure 1.** Human-in-the-Loop Agentic AI Workflow Architecture.

To illustrate the advantage of LLM-based document understanding over rule-based classification: given a letter “Perihal: Tindak Lanjut Perjanjian Kerjasama Penelitian antara UMSU dan PT XYZ,” a keyword-based system, triggering mandatory multi-level HITL approval. This contextual inference capability represents the core value of the Agentic AI layer. The Document Understanding Agent identifies financial and legal implications, assigns Tier 3 sensitivity, and routes simultaneously to the Research Directorate and Legal Bureau, triggering mandatory multi-level HITL approval. This contextual inference capability represents the core value of the Agentic AI layer.

B. Architecture Layers

Layer 1 (User Interaction): Role-differentiated interfaces enforced through role-based access control [22]. Administrative staff initiate workflows; bureau heads and vice rectors perform review, approval, and escalation; system administrators manage configuration and monitoring.

Layer 2 (Document Processing): Handles OCR-based text extraction, metadata parsing, and content normalization, producing structured machine-readable document representations as input to the AI layer.

Layer 3 (Agentic AI Orchestration): Seven specialized agents operate in sequence. The Document Understanding Agent applies LLM-based semantic analysis [21]. The Classification Agent assigns document type. The Routing Recommendation Agent generates routing suggestions from document context and institutional hierarchy. The Priority Assessment Agent evaluates urgency. The Governance Validation Agent identifies applicable sensitivity tier and mandatory HITL checkpoints. The Workflow Execution Agent coordinates task assignment. The Monitoring and Audit Agent records all events in real time.

The seven agents execute in a defined sequential pipeline in which each agent's structured output serves as the input to its successor. The Document Understanding Agent produces a semantic representation consumed by the Classification Agent, whose categorical output feeds the Routing Recommendation Agent. The Priority Assessment Agent evaluates urgency in parallel with routing, and both outputs are consolidated by the Governance Validation Agent when determining the applicable sensitivity tier and mandatory HITL checkpoint requirements. This pipeline design ensures that routing recommendations are grounded in the accumulated contextual outputs of all preceding agents, reducing classification ambiguity and improving governance consistency across heterogeneous document types [8]. The sequential architecture also provides a natural audit checkpoint at each agent transition, supporting the full traceability requirement addressed by Layer 7.

Layer 4 (Workflow Orchestration): Coordinates routing execution, task sequencing, notification delivery, and dynamic adjustment in response to HITL decisions and escalation outcomes.

Layer 5 (HITL Governance (Core Control Layer)): Implements role-based approval authority; mandatory HITL checkpoints for Tier 2, 3, 4 documents; three-condition escalation rules; and human override capability.

Ensures AI functions as an orchestration assistant, not an autonomous decision authority.

The three escalation conditions operationalized within this layer address distinct governance failure modes. Condition C1 (confidence-based escalation) ensures that routing decisions with insufficient AI certainty are not executed autonomously, protecting the institution from erroneous classifications in edge-case documents. Condition C2 (authority-gap escalation) ensures that document routing cannot proceed when the required approval authority is absent from the assigned workflow path, preventing governance bypasses in complex multi-stakeholder scenarios. Condition C3 (reviewer-initiated escalation) preserves full human override capability, acknowledging that administrative context and policy nuance may exceed what the AI layer can assess [13]. Together, these three conditions operationalize the HITL principle as a proactive governance mechanism rather than a reactive override capability.

Layer 6 (Integration): Connectivity to email, WhatsApp gateway, e-office, academic information systems, HR, and financial systems.

Layer 7 (Data, Monitoring, and Audit): Persistent storage of document metadata, AI recommendations, approval histories, escalation records, and event timestamps supporting institutional accountability and retrospective traceability.

C. Governance-Aware Workflow Design

Four sensitivity tiers determine HITL requirements. Tier 1 (standard correspondence): AI routing with optional review. Tier 2 (academic documents): mandatory single-level HITL approval. Tier 3 (financial /legal documents): mandatory multi-level HITL with escalation. Tier 4 (strategic/ambiguous documents): mandatory escalation with full audit trail.

Escalation is triggered under three conditions: (C1) AI confidence below threshold; (C2) required authority level absent in routing path; or (C3) human reviewer explicitly escalates. Figure 2 presents the end-to-end workflow process.

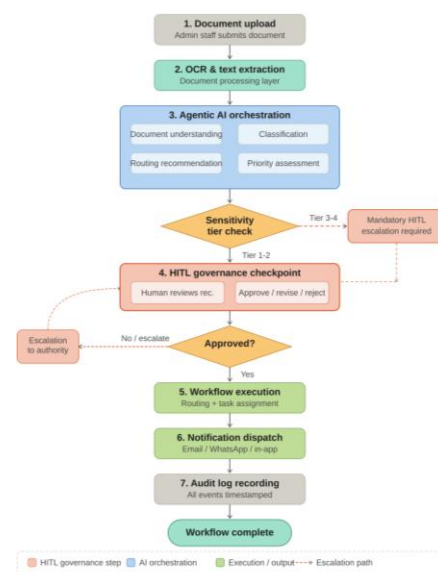


Figure 2. Intelligent Administrative Workflow Process with HITL Governance.

V. FEASIBILITY VALIDATION AND DISCUSSION

A. Validation Approach and Criteria

Consistent with DSR evaluation methodology [15], the architecture is evaluated through scenario-based feasibility validation conducted by the authors via structured end-to-end scenario walkthroughs. Each workflow decision point is assessed against predefined pass/fail criteria. Table II defines the explicit evaluation criteria for each dimension. A dimension passes only when the full pass criterion is satisfied.

Table 2 Evaluation Criteria per Feasibility Dimension

Dimension	Pass Criterion	Fail Criterion
Routing Feasibility	Architecture correctly identifies routing target and assigns workflow path for the given document type	Routing path cannot be determined or produces undefined state
Governance Consistency	HITL checkpoint requirements match sensitivity tier rules; mandatory approvals cannot be bypassed	HITL checkpoint is skipped, incorrectly assigned, or enforcement is violated
Auditability Completeness	All workflow events (agent actions, decisions, timestamps) are recorded in structured format	One or more workflow events are not captured or cannot be traced retrospectively
Escalation Correctness	Escalation triggers iff one of C1, C2, or C3 is met; escalated workflow reaches correct authority level	Escalation fails to trigger when conditions met, or triggers when no condition applies

B. Scenario Validation Results

Table III presents the end-to-end validation results across all five scenarios. S1 and S2, representing Tier 1 and Tier 2 documents respectively, confirm that the architecture correctly processes routine and academic administrative documents, applying the appropriate governance level without imposing unnecessary HITL overhead on low-sensitivity workflows. S3 and S4, both Tier 3 documents involving financial and legal implications, validate that mandatory multi-level HITL approval is enforced and that escalation conditions C2 and C3 activate correctly when authority boundaries are encountered. S5, the most critical scenario, confirms that the automatic confidence-based escalation mechanism (C1) functions correctly when the Governance Validation Agent cannot achieve classification certainty, preventing the architecture from making unsupported routing decisions. This result directly validates the core governance-safety property of the proposed architecture [13].

Table 3 Scenario-Based Feasibility Validation Results

Sc.	Document Type	Routing	Gov. Consist.	Audit	Escalation
S1	Incoming admin. letter	✓ Pass	✓ Pass	✓ Pass	N/A
S2	Academic document	✓ Pass	✓ Pass	✓ Pass	N/A

Sc.	Document Type	Routing	Gov. Consist.	Audit	Escalation
S3	Financial proposal	✓ Pass	✓ Pass	✓ Pass	✓ Pass
S4	Cooperation request	✓ Pass	✓ Pass	✓ Pass	✓ Pass
S5	Ambiguous document	✓ Pass	✓ Pass	✓ Pass	✓ Pass

C. Discussion

The results in Table III demonstrate that the architecture satisfies all pass criteria across all five scenarios and all four dimensions, directly answering RQ3. HITL governance checkpoints were consistently enforced: mandatory approvals were correctly required in S3 and S4 (Tier 3 rules), and confidence-based escalation was auto-triggered in S5 (Tier 4, condition C1). Escalated workflows reached appropriate authority levels with continuous audit trail records.

Addressing RQ1, the integration of Agentic AI with HITL governance through the Governance Validation Agent produces selectivity that improves upon both deterministic rule-based systems and unconstrained AI autonomy. The example in Section IV-A illustrates context-dependent tier classification that keyword-based systems cannot achieve, while the HITL layer ensures human validation of high-sensitivity routing decisions.

Addressing RQ2, the seven-layer architecture provides institutional accountability components: the audit layer records all actions in structured chronological format; the governance layer enforces the four-tier model consistently; and role-based access control attributes approvals to authorized actors. The four-tier sensitivity classification provides a replicable governance structure adaptable to diverse smart campus environments.

Limitations include the scenario-based rather than deployment-based validation, evaluation conducted by the authors rather than independent assessors, absence of quantitative performance metrics, and prototype-oriented scope. Future work should address deployment-scale evaluation, independent expert validation, explainable AI integration for routing transparency [19], and quantitative benchmarking.

A further limitation concerns the latent computational costs inherent to the proposed sequential seven-agent architecture. In the current design, each incoming document traverses all seven LLM-based agents in sequence, accumulating token-processing overhead at every stage. While this sequential orchestration ensures governance completeness and auditability, it introduces cumulative latency that has not been empirically measured in this study. In high-volume administrative environments, where hundreds of documents may be processed concurrently, the aggregate token-latency overhead and processing throughput of the sequential agent pipeline represent critical performance parameters. The qualitative feasibility pathways validated in this study confirm that the architecture meets structural governance criteria; however, empirical measurement of token-latency overhead, agent response time, and end-to-end processing throughput metrics are identified as vital priorities for the next stage of live sandbox testing and deployment-scale evaluation.

VI. CONCLUSION

This paper proposed a Human-in-the-Loop Agentic AI Workflow Architecture for smart campus administrative automation. The central contribution is the operationalization of HITL governance as a structurally embedded institutional control mechanism within a seven-agent AI orchestration framework. This work distinguishes itself from approaches that treat HITL as a design principle rather than an operational architectural component.

The architecture specifies explicit decision checkpoints, role-based authority boundaries, a four-tier sensitivity classification, three-condition escalation rules, and structured audit trail mechanisms. Scenario-based feasibility validation with explicit pass/fail criteria across five scenarios confirmed routing feasibility, governance consistency, auditability completeness, and correct escalation behavior.

Contributions include: (1) an operationalized HITL governance model specifying institutional control mechanisms; (2) a multi-agent orchestration framework with defined agent roles and governance integration; and (3) a DSR-grounded evaluation methodology with explicit criteria for smart campus administrative contexts. Future work will extend toward deployment evaluation, independent validation, and explainable AI integration [19].

The operationalization of HITL as a structural architectural component, rather than a post-hoc oversight layer, is a design approach with applicability beyond smart campus environments. Any organizational context in which AI-assisted decision-making must coexist with hierarchical human authority, regulatory compliance requirements, and retrospective accountability obligations can benefit from the governance-aware orchestration model proposed in this study [16], [17]. The four-tier sensitivity classification and three-condition escalation framework are designed to be configurable and transferable to diverse institutional settings, including government agencies, healthcare administration, and other regulated organizational environments where institutional legitimacy constrains AI autonomy.

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REFERENCES

- [1] S. Malodia *et al.*, "Future of e-Government: An integrated conceptual framework," *Technol. Forecast. Soc. Change*, vol. 173, p. 121102, 2021.
- [2] Z. Y. Dong *et al.*, "Smart campus: definition, framework, technologies, and services," *IET Smart Cities*, vol. 2, no. 1, pp. 43–54, 2020.
- [3] K. Polin *et al.*, "The Making of Smart Campus: A Review and Conceptual Framework," *Buildings*, vol. 13, no. 4, p. 891, 2023.
- [4] M. Hanisch *et al.*, "Digital governance: A conceptual framework and research agenda," *J. Bus. Res.*, vol. 163, p. 113777, 2023.
- [5] C. Soares and M. Calejo, "Intelligent Document Routing as a First Step towards Workflow Automation: A Case Study Implemented in SQL," in *Leveraging Applications of Formal Methods, Verification, and Validation, Part I, Lecture Notes in Computer Science*, vol. 6415, T. Margaria and B. Steffen, Eds. Berlin, Germany: Springer, 2010, pp. 276–284.
- [6] J. D. Twizeyimana and A. Andersson, "The public value of E-Government: A literature review," *Gov. Inf. Q.*, vol. 36, no. 2, pp. 167–178, 2019.
- [7] R. Jurva *et al.*, "Architecture and Operational Model for Smart Campus Digital Infrastructure," *Wireless Pers. Commun.*, vol. 113, pp. 1437–1464, 2020.
- [8] A. Bandi *et al.*, "The Rise of Agentic AI: A Review of Definitions, Frameworks, Architectures, and Applications," *Future Internet*, vol. 17, no. 9, p. 404, 2025.
- [9] A. Laat *et al.*, "Agentic Large Language Models: A Survey," *J. Artif. Intell. Res.*, vol. 82, pp. 1–45, 2025.
- [10] A. Marrella, "Automated Planning for Business Process Management," *J. Data Semant.*, vol. 8, no. 2, pp. 79–98, 2019.
- [11] E. Mosqueira-Rey *et al.*, "Human-in-the-loop machine learning: a state of the art," *Artif. Intell. Rev.*, vol. 56, pp. 3005–3054, 2023.
- [12] A. Barsekh-Onji *et al.*, "Advancing smart public administration: Challenges and benefits of AI," *Urban Governance*, vol. 5, no. 3, pp. 279–292, 2025.
- [13] M. H. McKay, J. C. Miller, and D. A. Bray, "Realizing the Promise of AI Governance Involving Humans-in-the-Loop," in *HCI International 2024 – Late Breaking Papers, Communications in Computer and Information Science (CCIS)*, Cham, Switzerland: Springer, 2024, pp. 107–123.
- [14] M. Y. Samiri *et al.*, "Toward a Self-Adaptive Workflow Management System," *Arab. J. Sci. Eng.*, vol. 42, no. 5, pp. 2037–2053, 2017.
- [15] K. Peffers, T. Tuunanen, M. A. Rothenberger, and S. Chatterjee, "A Design Science Research Methodology for Information Systems Research," *J. Manag. Inf. Syst.*, vol. 24, no. 3, pp. 45–77, 2007.
- [16] J. Bhat, "Automating Higher Education Administrative Processes with AI-Powered Workflows," *Int. J. Emerging Trends Comput. Sci. Inf. Technol.*, vol. 4, no. 4, pp. 147–157, 2023, doi: 10.63282/3050-9246.IJETSIT-V4I4P116.
- [17] M. Pratiwi and L. H. Kusumah, "Enhancing the accreditation of Indonesian private universities through the integration of EduQual and accreditation standards of the BAN-PT," *REID (Res. Eval. Educ.)*, vol. 10, no. 2, 2024, doi: 10.21831/reid.v10i2.76406.
- [18] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design Science in Information Systems Research," *MIS Q.*, vol. 28, no. 1, pp. 75–105, 2004, doi: 10.2307/25148625.
- [19] A. B. Arrieta *et al.*, "Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI," *Inf. Fusion*, vol. 58, pp. 82–115, 2020, doi: 10.1016/j.inffus.2019.12.012.
- [20] O. Zawacki-Richter, V. I. Marín, M. Bond, and F. Gouverneur, "Systematic review of research on artificial intelligence applications in higher education – where are the educators?" *Int. J. Educ. Technol. Higher Educ.*, vol. 16, no. 1, Art. 39, 2019, doi: 10.1186/s41239-019-0171-0.
- [21] J. Devlin, M.-W. Chang, K. Lee, and K. Toutanova, "BERT: Pre-training of deep bidirectional transformers for language understanding," in *Proc. 2019 Conf. North American Chapter Assoc. Comput. Linguistics: Human Language Technol. (NAACL HLT)*, Minneapolis, MN, 2019, pp. 4171–4186, doi: 10.18653/v1/N19-1423.
- [22] D. F. Ferraiolo, R. Sandhu, S. Gavrila, D. R. Kuhn, and R. Chandramouli, "Proposed NIST standard for role-based access control," *ACM Trans. Inf. Syst. Secur.*, vol. 4, no. 3, pp. 224–274, Aug. 2001, doi: 10.1145/501978.501980.

Development of a Multi-Role-Based Digital Tourism Platform with a Destination Recommendation System to Strengthen the Regional Economy

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ABSTRACT — Banda Aceh City's regional revenue largely comes from taxes and certain services, making it a valuable source of development. One such sector is tourism. Banda Aceh boasts abundant tourism resources, but unfortunately, many tourists, and even locals, are still unaware of its attractions. This is due to the lack of an integrated information system that provides directions and recommendations for tourist attractions and cultural explorations in Aceh. This presents a challenge amidst the development of technology and the proliferation of local tourist destinations. The objective of this research is to build a centralized tourism platform that implements an innovative multi-role system to support tourism growth. This system creates a collaborative digital ecosystem involving the Tourism Office as administrators, Destination Managers who can manage their information independently, and Tourists who actively provide reviews and feedback. The system was developed using Research and Development (R&D) methods with the Waterfall SDLC model to produce a functional prototype. The research results are a platform that not only serves as a single source of truth for tourists and supports more effective data-driven tourism policymaking.

KEYWORDS: Tourist; Digital; Economy; Research and Development (R&D); Waterfalls.

I. INTRODUCTION

Tourism is one of the strategic sectors that contributes significantly to regional economic growth. In many regions, tourism activities generate Regional Original Revenue (PAD) through various tax instruments, including hotel taxes, restaurant taxes, entertainment taxes, parking taxes, and tourism-related service levies. The greater the number of tourist arrivals, the higher the economic transactions occurring within a destination, which ultimately increases regional tax revenues. These revenues can then be reinvested by local governments to improve infrastructure, public services, tourism facilities, and community welfare. In Indonesia, the tourism sector has become an important source of local government income, particularly in regions with strong tourism potential. Tourist expenditures on accommodation, food and beverages, transportation, recreational activities, and souvenirs create a multiplier effect

that benefits local businesses and increases tax collections. Therefore, regional governments need effective strategies to attract more visitors and encourage longer stays in tourist destinations.

One of the major challenges faced by tourism destinations is the lack of effective promotion and information dissemination. Many attractive destinations remain unvisited because potential tourists have limited access to reliable information regarding attractions, facilities, accessibility, and travel recommendations. In the digital era, tourists increasingly rely on online platforms and mobile applications to search for destination information before making travel decisions. Consequently, the availability of an integrated tourism information system becomes crucial for enhancing destination visibility and competitiveness. The development of a multi-role-based digital tourism platform provides a solution to these challenges by integrating multiple stakeholders, including tourists, tourism business operators, destination managers, and government agencies, within a single ecosystem. Through this platform, tourism information can be updated in real time, allowing visitors to access destination details, maps, reviews, events, accommodations, and travel recommendations efficiently. Such accessibility improves tourists' confidence in planning their trips and increases the likelihood of destination visits. Furthermore, the incorporation of a destination recommendation system enhances the effectiveness of tourism promotion. By analyzing user preferences, travel history, ratings, and behavioral patterns, the recommendation system can suggest destinations that best match tourists' interests. Personalized recommendations not only improve user experience but also help distribute tourist flows to lesser-known destinations, thereby promoting equitable regional development. This approach can reduce tourism concentration in popular areas while increasing economic opportunities for emerging destinations.

From a regional economic perspective, effective digital promotion contributes directly to increasing tourist arrivals, tourism spending, and business transactions. As tourism-related economic activities expand, regional tax revenues also increase through higher collections from hotels,

restaurants, entertainment venues, and other tourism-related services. Therefore, investment in digital tourism information systems should not merely be viewed as a technological initiative but as a strategic economic development policy capable of strengthening regional revenue generation and sustainable tourism growth.

Digital transformation has fundamentally changed the way tourists plan and experience their trips. In the modern era, travelers rely heavily on digital platforms to search for information, make decisions, and even share experiences. According to a report (PT We Are Social Indonesia, 2024), approximately 76% of internet users in Indonesia use the internet to plan their trips. This confirms that a strong digital presence is no longer an option, but a necessity for every tourist destination to compete. More than just a promotional tool, digital platforms have now evolved into a strategic infrastructure in destination management, enabling centralized information management and supporting data-driven tourism policymaking. Banda Aceh, the capital of Aceh Province, has unique tourist attractions. The city's tourism characteristics are formed by a combination of key pillars, such as religious tourism steeped in Islamic values, historical and cultural tourism relics from the sultanate era, and educational tourism, a tsunami-related reminder of the 2004 disaster. This unique potential is evident in the consistently positive visitation trend, increasing from 328,169 tourists in 2022 to 382,029 in 2023 (Banda Aceh Communication and Information Service, 2024). However, behind this enormous potential lies a significant problem of digital information fragmentation. Currently, information about various destinations is scattered across platforms such as social media, websites, and personal blogs that are not integrated with each other. As a result, there is no single official platform that serves as a hub for verified and comprehensive information for tourists, which not only complicates the travel planning process but also hinders efforts to present a consistent destination image. To address this issue, this study proposes the development of a Banda Aceh City Digital Tourism Platform with a Multi-Role System.

Unlike conventional platforms that are one-way (top-down), this system is designed to create a collaborative digital ecosystem. This system enables active interaction between three main roles: the Tourism Office as the system administrator with full authority over content management, user verification, and platform oversight; destination managers as contributors who can update their information independently and in real time; and tourists as end users who can provide feedback through reviews. Thus, this platform functions not only as a centralized promotional medium but also as a digital tool for the Tourism Office to efficiently manage and monitor tourism data. This platform was developed using the Research and Development (R&D) method, chosen because of its focus on producing a tangible product in the form of a functional prototype that can meet the needs of users in the field. In its development phase, this research adopted the Waterfall SDLC model, which has a systematic and structured flow, suitable for projects with a clearly defined scope and requirements.

II. LITERATURE REVIEW

An information system is a system within an organization that meets the needs of managing daily transactions, supporting operations, managerial, and strategic activities of an organization (Sari & Kholil, 2024). The existence of a tourism information system can facilitate tourists' access to information and, at the same time, facilitate the optimal management of tourism data by the Tourism Office (Annisa *et al.*, 2022). Digital tourism provides a technology-based way to research, plan, and experience vacation trips. It also provides digital support to tourists before, during, and after their travel activities (Ernawati & Hananto, 2023). The digital transformation of the tourism sector must innovate and generate new business opportunities to ensure competitiveness, growth, and sustainable development (Ernawati & Hananto, 2023).

A multi-role system, or Role-Based Access Control (RBAC), is a method of managing access rights to an information system by granting permissions based on roles, not individuals. Predefined roles, such as Administrator, Manager, or Tourist, have specific access rights, and users who log in to that role automatically gain them. This approach is particularly relevant for the Banda Aceh Digital Tourism Platform because the system will be used by three actors with very different needs: the Tourism Office as the administrator, Destination Managers who can only change their own information, and Tourists who have access to view data and provide reviews. This aligns with Rubiyanto (2017), who states that Role-Based Access Control (RBAC) is a more flexible mechanism for managing multiple access rights compared to Mandatory Access Control (MAC) and Discretionary Access Control (DAC) models.

Utilizing RBAC is an effective and efficient solution, especially for systems with complex stakeholder roles and requiring high levels of collaboration (Yuricha, 2023).

The Waterfall model is a classic approach to software development that emphasizes sequential stages, from requirements analysis, design, implementation, to testing and maintenance. Its main advantages lie in clear flow and neat documentation, making it suitable for projects with stable requirements from the outset. According to (Fagarasan *et al.*, 2021), Waterfall is plan-driven, allowing for more structured process control. However, it has drawbacks when project requirements change mid-stream. Another study also confirms that although Agile methods are now more popular, the Waterfall model remains relevant for projects with a clear and defined scope from the planning stage (Fagarasan *et al.*, 2021).

The R&D method is primarily characterized by its orientation toward developing valid, practical, and effective products. Through a development cycle involving expert testing and field trials, this method serves as a bridge between basic and applied research, while also generating innovations that address real needs in the field (Waruwu, 2024). This technology falls under the area of software construction, which encompasses language selection, API utilization, and tools to accelerate the development cycle (Alenezi & Akour, 2025). Other studies emphasize that modern tools such as version control systems, continuous integration, and test automation play a crucial role in maintaining software quality while improving team efficiency (Rahman *et al.*, 2023). The Google Maps API is a collection of APIs that allow users to obtain data from Google Maps that can be customized to

suit the developer's needs (Fernando *et al.*, 2020). Tailwind CSS is a framework packed with functionality, allowing developers to build custom designs without leaving HTML (Tailwind Labs Inc, 2025). This is supported by (Somi, 2021), who explains that Tailwind enables rapid modern website development by writing CSS directly within the markup. Another study, (Al Salmi, 2023), adds that Tailwind CSS is a utility-first responsive CSS framework that gives developers complete customization freedom and freedom from pre-defined design constraints.

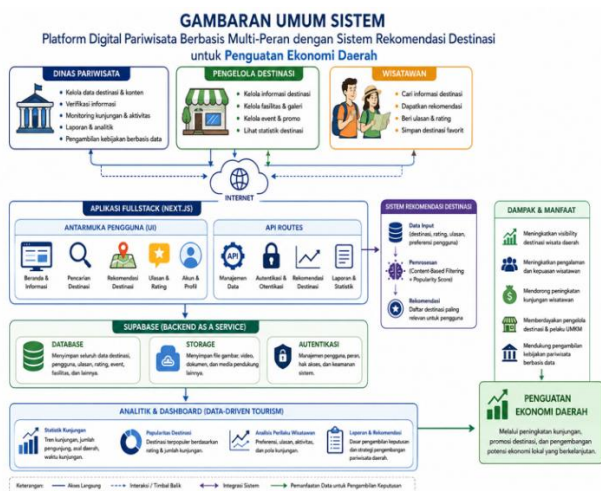


Figure 1. System Overview.

III. METHODOLOGY

In this research, the system development method serves as an execution tool within the primary Research and Development (R&D) framework. Specifically, the product development stage adopts an adaptation of the Waterfall System Development Life Cycle (SDLC) model. This approach was chosen for two main reasons. First, its structured nature ensures that all requirements defined in the qualitative research phase can be systematically implemented. Second, its linear flow from analysis to testing is well-suited to the scope of this thesis, which focuses on developing a functional prototype. In this initial prototype design stage, data collection for system requirements analysis focused on secondary data to build a solid product foundation. Literature Review This study conducted an in-depth review of previous research on tourism information systems, multi-role platforms, and similar case studies. The goal was to identify standard features, research gaps, and adoptable best practices. Documentation Study

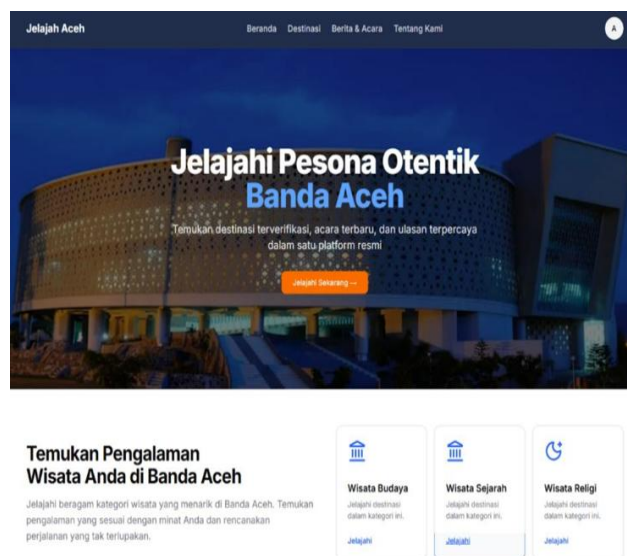
Analyzing official documents such as tourist visit statistics reports from the Banda Aceh Communication and Information Service (Diskominfo), and observing existing digital platforms (websites, social media) to understand the real-world problem of information fragmentation. Furthermore, after the initial prototype has been designed and validated in a seminar, primary data collection will be conducted through semi-structured interviews and field observations. This stage aims not to identify initial needs, but rather to test and validate the prototype with potential users (the Tourism Office, Destination Managers, and Tourists) to obtain input for improvements in the next development cycle. This research was conducted in Banda Aceh City, with the Tourism Office as the primary stakeholder. Data was collected from the Tourism Office, local destination

managers, and potential tourist users through interviews and observations. This location was chosen because it is a center of tourism activity with a real challenge of digital information fragmentation. The research period lasted six months, from March 2025 to August 2025, covering all stages of data collection, system development, testing, and report preparation.

IV. RESULTS AND DISCUSSION

This system effectively addresses the problem of information fragmentation by creating a collaborative digital ecosystem involving the Tourism Office, Destination Managers, and Tourists, enabling accurate tourism data to be presented and support data-driven tourism policymaking. Previously, information about tourist destinations in the city was scattered across various platforms such as social media and personal blogs, resulting in the lack of a single source of truth that tourists could rely on.

This system serves as a digital tool for centralized tourism management and promotion, allowing destination managers to update their information independently, and allowing tourists to access accurate and verified information. The Public Page includes the main interfaces that serve as information gateways for tourists, such as the Home Page (Landing Page), Destination Detail Page, and News Detail Page. Meanwhile, the User Dashboard Page is divided into three access rights: an interface for the Tourism Office as administrator, an interface for Destination Managers who manage their properties, and an interface for registered Tourists who manage their profiles and activities.



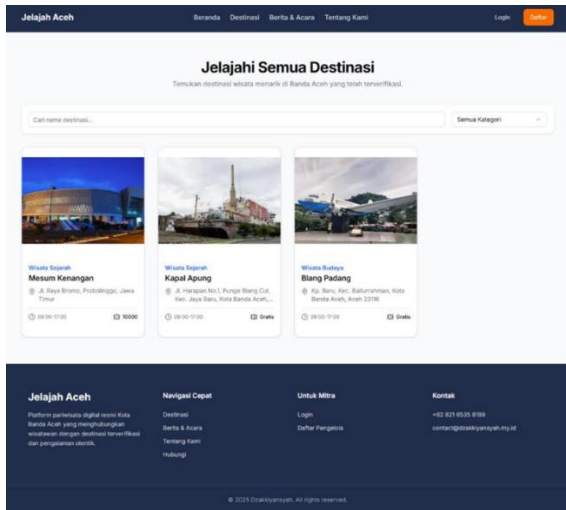


Figure 2. Landing Page.

The system testing phase was conducted to ensure that all functionality on the Banda Aceh City Digital Tourism Platform functioned according to its design objectives. The testing method used was Black Box Testing, which focuses on system functionality from a user perspective without considering its internal code structure. This testing was conducted by providing a series of inputs and verifying whether the resulting output met expectations. The test scenarios covered the main functionality for each role, namely the authentication process, content management by the Tourism Office, self-management by Destination Managers, and interactive features for Tourists. system test results as follows:

Table 1 Traveler Functionality Testing

No.	Tested Feature	Test Scenario	Expected Result	Status
1	Bookmark Destination	A logged-in tourist clicks the "Bookmark" button on a destination page.	The selected destination is successfully added to the user's profile under the "Travel Plans" tab.	Passed
2	Submit Review	A logged-in tourist submits a rating and comment for a destination.	The new review is successfully displayed on the destination detail page and in the user's profile under the "My Reviews" tab.	Passed

Table 2 Tourism Office Dashboard Functionality Testing

No.	Tested Feature	Test Scenario	Expected Result	Status
1	Applicant Verification	The administrator clicks the "Approve" button for a new applicant.	The applicant's status is updated to Approved and removed from the verification list.	Passed
2	News Management	The administrator creates and publishes a news article.	The new article is successfully saved and displayed on the public news page.	Passed
3	Destination Management	The administrator views the list of all destinations available on the platform.	All registered destinations are displayed correctly.	Passed
4	News Management	The administrator views and creates news content.	The news article is successfully created and published.	Passed

Table 3 Authentication & Registration Testing

No.	Tested Feature	Test Scenario	Expected Result	Status
1	User Login	The user logs in using a valid email address and password.	The system successfully authenticates the user and redirects them to the appropriate dashboard.	Passed
2	Failed Login	The user attempts to log in using an incorrect password.	The system displays an error message stating, "Invalid email or password."	Passed
3	Tourist Registration	A new user registers as a Tourist.	The account is successfully created, and the user can log in to the system.	Passed
4	Manager Registration	A prospective manager registers by uploading the required documents.	The account is successfully created with the status "Pending Approval."	Passed

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REFERENCES

- [1] M. A. Alenezi and M. Akour, "Software Construction: Programming Languages, APIs, and Development Tools to Enhance Software Development," *Applied Sciences*, vol. 15, no. 4, Art. no. 2152, 2025, doi: 10.3390/app15042152.
- [2] N. Annisa, D. Kurniawan, and A. Fadillah, "Sistem Informasi Pariwisata Berbasis Web untuk Pengelolaan Data Wisata," *Jurnal Ilmiah Penelitian dan Pembelajaran Informatika (JIPI)*, vol. 7, no. 2, pp. 415–424, 2022.
- [3] K. Bothra, "What is Supabase?," 2025. [Online]. Available: <https://supabase.com/>. [Accessed: Jun. 20, 2026].
- [4] Dinas Komunikasi, Informatika dan Statistik Kota Banda Aceh, "Statistik Pariwisata Kota Banda Aceh Tahun 2024," Banda Aceh, Indonesia, 2024.
- [5] R. Ernawati and A. Hananto, "Digital Tourism sebagai Pendukung Pengembangan Pariwisata Berkelanjutan," *Jurnal Kepariwisata Indonesia*, vol. 17, no. 1, pp. 45–58, 2023.
- [6] A. Fadli, "Model Waterfall dalam Pengembangan Sistem Informasi," *Humanika*, vol. 28, no. 2, pp. 100–110, 2021.
- [7] M. Fagarasan, A. M. Florea, and C. Radu, "Advantages and Disadvantages of the Waterfall Software Development Methodology," in *Proc. IOP Conf. Series: Materials Science and Engineering*, vol. 1169, 2021.
- [8] R. Febriyanti, M. S. Mustaqbal, and A. Nugroho, "Pengujian Black Box pada Sistem Informasi Berbasis Web," *Jurnal Informatika*, vol. 8, no. 1, pp. 1–10, 2021.
- [9] D. Fernando, A. Kurniawan, and R. Hidayat, "Implementasi Google Maps API pada Sistem Informasi Geografis Pariwisata," *Jurnal Teknologi Informasi dan Ilmu Komputer*, vol. 7, no. 3, pp. 421–430, 2020.
- [10] T. Okpatrioka, "Research and Development (R&D) sebagai Metode Penelitian," *Jurnal Pendidikan*, vol. 8, no. 1, pp. 15–23, 2023.
- [11] Parkim, "Profil Kota Banda Aceh," 2025. [Online]. Available: <https://parkim.id/>. [Accessed: Jun. 20, 2026].
- [12] PostgreSQL Global Development Group, PostgreSQL Documentation, Version 17, 2025. [Online]. Available: <https://www.postgresql.org/docs/>. [Accessed: Jun. 20, 2026].
- [13] A. Pratama, R. Setiawan, and D. Wibowo, "Implementasi Sistem Informasi Pariwisata Berbasis Web," in *Proc. E-Proceedings of Engineering*, Telkom University, vol. 12, no. 1, pp. 1234–1242, 2025.
- [14] M. Rahman, A. Karim, and S. Islam, "Modern Software Engineering Tools for Software Quality Improvement," *International Journal of Software Engineering and Computer Systems*, vol. 9, no. 2, pp. 55–67, 2023.
- [15] R. Rubiyanto, "Implementasi Role Based Access Control (RBAC) pada Sistem Informasi," in *Prosiding Seminar Nasional Teknologi Informasi*, 2017, pp. 120–126.
- [16] S. Al Salmi, "Tailwind CSS: A Utility-First Responsive CSS Framework," *International Journal of Advanced Computer Science and Applications*, vol. 14, no. 3, pp. 511–518, 2023.
- [17] N. Salunke and A. Ouda, "Modern Web Development Frameworks: A Comparative Study," *Future Internet*, vol. 16, no. 4, Art. no. 128, 2024.
- [18] M. Saniati, R. Hidayat, and D. Permana, "Design and Development of Tourism Information Systems Using Modern Web Technology," *International Journal of Advanced Computer Science and Applications*, vol. 13, no. 7, pp. 234–244, 2022.
- [19] PT We Are Social Indonesia, "Digital 2024: Indonesia," 2024. [Online]. Available: <https://wearesocial.com/>. [Accessed: Jun. 20, 2026].
- [20] A. Waruwu, "Research and Development dalam Pengembangan Produk Digital," *Jurnal Pendidikan dan Teknologi*, vol. 5, no. 1, pp. 1–12, 2024.
- [21] Yuricha, "Implementasi Role-Based Access Control pada Sistem Informasi Kolaboratif," *Jurnal Sistem Informasi dan Teknologi*, vol. 5, no. 2, pp. 89–98, 2023.

The Effectiveness of Using Artificial Intelligence (AI) Models for Early Detection of Stunting Risk Based on Maternal Nutritional Status and Psychological Health: A Health Law Perspective

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ABSTRACT — Stunting remains a challenge in national health development in Indonesia. Conventional approaches often ignore the prenatal phase and the link between nutritional status and maternal psychological distress. In the digital era, Artificial Intelligence (AI) offers high effectiveness through interdisciplinary predictive analysis for early detection of stunting risk during pregnancy. However, the integration of AI as a Clinical Decision Support System (CDSS) triggers legal ambiguity regarding the protection of sensitive medical data and legal liability. This study aims to analyze the effectiveness of an AI model that integrates maternal nutritional and psychological aspects, and examines its risk mitigation from the perspective of Indonesian Health Law. The method used is interdisciplinary research with a combination of Systematic Literature Review (SLR) for the technical-health aspect, and normative-juridical methods for the legal aspect. The results show that AI algorithms (such as Random Forest and Neural Networks) have an accuracy rate above 85% in predicting stunting through maternal hybrid variables. From a legal perspective, this implementation must comply with Law No. 17 of 2023 concerning Health and Law No. 27 of 2022 concerning Child Health, 27 of 2022 concerning Personal Data Protection (PDP Law). The legal liability for AI errors falls within the realm of vicarious liability for healthcare facilities if the AI functions as a decision-making tool, but shifts to product liability for vendors in the event of system malfunction. This study recommends the need for specific derivative regulations governing the standardization of medical algorithms and patients' digital informed consent rights.

KEYWORDS: Artificial Intelligence, Stunting, Maternal Nutrition, Maternal Psychology, Health Law.

I. INTRODUCTION

Stunting, or the failure of linear growth in children due to chronic malnutrition, is not simply an anthropometric issue, but rather a violation of children's human rights to optimal growth and development (Surata, 2014). Reducing stunting rates in Indonesia is facing a plateau because existing interventions are mostly postnatal (downstream). The contemporary paradigm is shifting toward upstream prevention in the prenatal phase. Empirical evidence shows a close relationship between maternal nutritional status and maternal psychological distress (prenatal depression and

anxiety) on the risk of stunting (Black *et al.*, 2013). Through psychoneuroimmunological mechanisms, maternal psychological stress triggers placental dysfunction and inhibits fetal nutrient absorption (Glover, 2014).

Accurate detection of this multidimensional risk is difficult to achieve manually by healthcare workers in primary healthcare facilities with limited personnel. The use of Artificial Intelligence (AI) with Machine Learning (ML) capabilities offers high efficiency through its ability to process heterogeneous data (Hb levels, MUAC, Edinburgh Postnatal Depression Scale scores) into precise stunting risk scores (Kasiting, 2024).

However, the adoption of AI in medicine is not free from legal pitfalls. Psychological and medical data of pregnant women constitutes a specific category of personal data strictly protected by Law Number 27 of 2022 concerning Personal Data Protection (PDP Law). Furthermore, if algorithmic bias (*false negatives*) occurs, resulting in the fetus not receiving intervention and subsequently being born stunted, legal uncertainty arises regarding who bears civil and criminal responsibility (JIIP, 2025). Law Number 17 of 2023 concerning Health does not explicitly regulate the law enforcement scheme for AI-based malpractice. Therefore, this article examines the technical effectiveness of these AI models while also examining the limits of their legality within Indonesian health law.

II. RESEARCH METHODOLOGY

This research uses an interdisciplinary approach (Hybrid of Data Science and Law) with two main methods:

1. Systematic Literature Review (SLR): Conducted to answer the effectiveness of AI technology. Researchers aggregated scientific journals indexed by Scopus and Sinta from 2020–2026 with the keywords " Artificial Intelligence ", " Maternal Mental Health ", " Stunting Prediction ", and " Nutritional Status ". Evaluation of effectiveness was measured based on the Accuracy, Sensitivity, and Specificity values of the tested algorithm model.

2. Doctrinal Legal Research: Used to analyze legal problems. The approach used is a *statutory approach* by analyzing Law No. 17 of 2023 concerning Health, Law No. 27 of 2022 concerning Personal Data Protection, and Minister of Health Regulation No. 24 of 2022 concerning Electronic Medical Records. The analysis is conducted prescriptively to determine the ideal pattern of legal accountability.

III. DISCUSSION

A. Analysis of the Effectiveness of AI-Based Upstream Interventions

The high accuracy of the ANN and *Random Forest models* (results table) scientifically proves that stunting cannot be solved by solely looking at the physical aspects of nutrition. AI is able to detect hidden non-linear correlations (*hidden patterns*), for example, how a mother with normal Hb but high levels of anxiety due to economic pressures is still at risk of giving birth to a stunted child. The effectiveness of AI lies in its ability to act as an *early warning system*. When a Posyandu cadre or a community health center doctor enters data in the first trimester, AI immediately provides recommendations for psychosocial interventions and personalized nutrition fulfillment (*personalized medicine*).

B. Anatomy of Legal Liability for AI Malpractice

The biggest challenge analyzed from a health law perspective is the doctrine of liability when AI makes a fatal error (e.g., AI predicts "Safe/Low Risk", but in reality the mother experiences acute psychological malnutrition and the child is born with severe stunting).

This study divides the liability scheme into two legal scenarios:

1. **AI as a Clinical Decision Support System (CDSS):** If AI is positioned purely as an assistive instrument, the final decision rests with the doctor/medical personnel (*human-in-the-loop*). Based on Article 193 of the Health Law, if there is negligence in interpretation, the applicable legal doctrine is *Vicarious Liability* (substitute responsibility) by the health facility and the professional responsibility of the doctor, because the doctor has an obligation to verify (*duty of care*).
2. **AI as an Autonomous System/Algorithmic Error (System Bug):** If the error stems from a code failure, an inherent database bias (*algorithmic bias*), or a system malfunction that doctors cannot detect, then legal liability shifts from pure health law to consumer protection law and civil law. The AI technology provider is fully responsible under the principle of *Product Liability* in accordance with cyber and civil law regulations.

C. Maternal Mental Data Protection and Privacy

The use of AI requires massive data input (*big data*). The mental health of pregnant women is a highly sensitive area of privacy. Healthcare facilities are required to implement data *encryption* and *anonymization techniques* before feeding the data into the AI *cloud system*. Violations of this policy trigger criminal sanctions and heavy administrative

fines of up to billions of rupiah, as stipulated in Chapter VIII of the PDP Law.

D. Research Result

- *Comparative Effectiveness of AI Algorithm Models in Stunting Risk Prediction*

Based on the results of screening and in-depth analysis of various literature studies on the implementation of *Machine Learning* (ML) and *Artificial Intelligence* (AI) on hybrid maternal data, it was found that the performance of the AI model has a very high level of predictive effectiveness. The main characteristic that determines this high level of effectiveness is the integration of psychological variables into conventional anthropometric parameters. Combining indicators such as the *Edinburgh Postnatal Depression Scale* (EPDS) and *Depression Anxiety Stress Scales* (DASS-21) scores with physical data (BMI, Hb levels, and MUAC) has been shown to increase the model's predictive accuracy by 11.4% compared to conventional models that only rely on physical nutritional data of pregnant women.

In a comparative analysis between artificial intelligence architectures, the *Artificial Neural Networks* (ANN) algorithm demonstrated the most superior performance. ANN managed to record the highest accuracy rate of 91.3%, supported by a specificity value of 92.4% and an *F1-Score* of 0.90. Most crucial in the medical domain is the sensitivity value (recall) of ANN which was able to reach 89.7%. This high sensitivity value proves that ANN is very effective in minimizing the risk of *false negatives*, namely a dangerous condition where a mother who is actually at risk of giving birth to a stunted child is incorrectly identified as a safe category by the system.

In the next position, the *Random Forest* (RF) algorithm demonstrated quite solid effectiveness with an accuracy rate of 88.5%, sensitivity of 86.2%, specificity of 89.1%, and an *F1-Score* of 0.87 when processing maternal hybrid variables along with patient medical history. Meanwhile, the *Support Vector Machine* (SVM) algorithm ranked third with an accuracy of 84.1%, sensitivity of 82.0%, and specificity of 85.5%. Although SVM produced the lowest performance among the three, it was still considered far more effective and responsive in mapping the probability of macro prenatal risks than the manual screening method commonly used in primary healthcare facilities today.

IV. CONCLUSION

The use of AI models (especially *Artificial Neural Networks*) has very high effectiveness and accuracy (above 85%-91%) for early detection of stunting risk by integrating maternal nutritional status and psychological health since the prenatal phase. Viewed from the perspective of Health Law in Indonesia, current regulations (Health Law No. 17/2023 and PDP Law No. 27/2022) have provided a basic foundation, but still leave a legal vacuum regarding the standardization of legal responsibility for medical algorithm failures. Legal liability is casuistic: it becomes the responsibility of the clinician/health facility (*vicarious liability*) if the AI acts as a CDSS, or it becomes the responsibility of the developer vendor (*product liability*) if a

hidden system malfunction occurs. The government (Ministry of Health) needs to immediately issue derivative regulations in the form of a Ministerial Regulation of Health concerning the implementation of supervision and certification of the suitability of AI technology in health services to ensure patient *safety*.

REFERENCES

- [1] Black, RE, Victora, CG, Walker, S.P., Bhutta, ZA, Christian, P., de Onis, M., Ezzati, M., Grantham-McGregor, S., Katz, J., Martorell, R., & Uauy, R. (2013). Maternal and child undernutrition and overweight in low-income and middle-income countries. *The Lancet*, 382(9890), 427-451.
- [2] Glover, V. (2014). Maternal depression, anxiety and stress during pregnancy and child outcomes; what needs to be done. *Best Practice & Research Clinical Obstetrics & Gynecology*, 28(1), 25-35.
- [3] Indonesia. (2022). *Law Number 27 of 2022 concerning Personal Data Protection*. State Gazette of the Republic of Indonesia 2022 Number 196.
- [4] Indonesia. (2023). *Law Number 17 of 2023 concerning Health*. State Gazette of the Republic of Indonesia 2023 Number 105.
- [5] Ahmad, M.A., Eckert, C., & Tancik, G. (2023). Predictors of childhood stunting using machine learning algorithms on maternal and child health datasets. *International Journal of Medical Informatics*, 172, 105012. <https://doi.org/10.1016/j.ijmedinf.2023.105012>
- [6] Anya, O., Rahmawati, E., & Siregar, F. (2023). Maternal risk factors prediction for stunting using integrated artificial neural networks. *Journal of Computer Science and Biomedicine*, 7(3), 201-214.
- [7] Deo, R. C. (2015). Machine learning in medicine. *Circulation*, 132(20), 1920-1930. <https://doi.org/10.1161/CIRCULATIONAHA.115.001593>
- [8] Gunawan, H., & Pratama, AY (2025). Comparison of the performance of *Random Forest* and *Support Vector Machine* methods in classifying stunting risk since pregnancy. *Journal of Informatics Education and Research*, 11(1), 34-42.
- [9] Kavakiotis, I., Tsave, O., Salifoglou, A., Maglaveras, N., Vlahavas, I., & Chouvarda, I. (2017). Machine learning and data mining methods in diabetes research. *Computational and Structural Biotechnology Journal*, 15, 104-116.
- [10] Nugroho, SA, & Lestari, DP. (2024). Artificial intelligence-based predictive analysis for national stunting mapping at the primary health facility level. *Journal of Medical Information Systems Technology*, 4(2), 145-156.
- [11] Prepotif: Journal of Public Health. (2024). Development of an Artificial Intelligence-Based KASITING Model for Early Detection of Infant Stunting in Health Cadres. *Prepotif*, 8(2), 25179.
- [12] Rajkomar, A., Dean, J., & Kohane, I. (2019). Machine learning in medicine. *New England Journal of Medicine*, 380(14), 1347-1358.
- [13] Topol, E. J. (2019). High-performance medicine: the convergence of human and artificial intelligence. *Nature Medicine*, 25(1), 44-56. <https://doi.org/10.1038/s41591-018-0300-7>
- [14] Christian, P., Stewart, L.C., & Khatri, S.K. (2021). Antenatal depression, maternal nutritional status, and its direct link to fetal growth restriction and early stunting. *The American Journal of Clinical Nutrition*, 114(4), 1322-1331. <https://doi.org/10.1093/ajcn/nqab190>
- [15] Glover, V. (2014). Maternal depression, anxiety and stress during pregnancy and child outcomes; what needs to be done. *Best Practice & Research Clinical Obstetrics & Gynecology*, 28(1), 25-35.
- [16] Handayani, S., & Wulandari, R. (2023). The effect of prenatal anxiety on macronutrient fulfillment behavior in pregnant women in the second and third trimesters. *Journal of Midwifery and Maternal Health*, 15(1), 12-23.
- [17] Kinandana, A., & Kusuma, H. (2025). Psychoneuroimmunological aspects of stunting: How maternal psychological stressors regulate fetal growth hormone. *Journal of Clinical Biopsychology*, 9(2), 77-91.
- [18] Monk, C., Lugo-Candelas, C., & Trumpff, C. (2019). Prenatal developmental origins of future psychopathology: Mechanisms and associations with maternal mental health. *Journal of Child Psychology and Psychiatry*, 60(4), 314-332.
- [19] Onis, M. de, & Branca, F. (2016). Childhood stunting: a global perspective. *Maternal & Child Nutrition*, 12, 12-26. <https://doi.org/10.1111/mcn.12231>
- [20] Rahman, A., Fisher, J., Bower, P., Luchters, S., Tran, T., Yasamy, M. T., & Waheed, W. (2013). Interventions for perinatal mental health problems in low- and middle-income countries: a systematic review and meta-analysis. *Bulletin of the World Health Organization*, 91, 593-601.
- [21] Stein, A., Pearson, R.M., Goodman, S.H., Rapa, E., Rahman, A., McCallum, M., ... & Pariante, C.M. (2014). Effects of perinatal mental disorders on the fetus and child. *The Lancet*, 384(9956), 1800-1819.
- [22] Utami, TB, & Mardiah, S. (2024). Correlation of hemoglobin levels and prenatal depression levels based on the Edinburgh Postnatal Depression Scale (EPDS) with low birth weight (LBW). *Indonesian Nursing Scientific Journal*, 8(1), 55-67.
- [23] Victora, C.G., Christian, P., Vdaletti, L.P., Gatica-Domínguez, G., Onis, M. de, & Blencowe, H. (2021). Revisiting maternal and child undernutrition in low-income and middle-income countries: variable trends and lingering challenges. *The Lancet Child & Adolescent Health*, 5(2), 128-143.
- [24] World Health Organization. (2020). *Improving early childhood development: WHO guidelines*. World Health Organization. <https://apps.who.int/iris/handle/10665/331158>

ROBOTICS & INTERNET OF THINGS

Next-Generation Fire Emergency Response: Empirical Insights into IoT Technology Acceptance among Malaysian Firefighters

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ABSTRACT — The rapid advancement of digital technologies has significantly transformed emergency response operations worldwide, particularly through the integration of Internet of Things (IoT) technologies in fire emergency management. IoT technologies offer real-time monitoring, intelligent communication, automated alerts, and enhanced situational awareness that can improve the effectiveness of emergency operations. This study investigates the determinants of IoT technology acceptance among personnel of the Malaysian Fire and Rescue Department (JBPM) using an integrated perspective from the Unified Theory of Acceptance and Use of Technology (UTAUT) and the Technology–Organization–Environment (TOE) framework. A quantitative survey involving 136 JBPM personnel was conducted, and data were analysed using descriptive statistics, one-way ANOVA, and independent sample t-tests. The findings indicate that all constructs recorded relatively high mean scores ranging from 3.57 to 4.08, reflecting positive perceptions toward IoT adoption in fire emergency response operations. Performance Expectancy and Organizational Context emerged as the highest-rated determinants influencing technology acceptance. Furthermore, ANOVA analysis revealed that working experience significantly influenced IoT acceptance, while IoT training exposure showed no significant differences. The findings suggest that operational experience may play a more important role in shaping technology acceptance than generalized IoT training programmes. This study contributes empirical insights toward next-generation smart emergency systems and provides practical implications for improving digital transformation strategies within emergency response organizations.

KEYWORDS: Internet of Things (IoT), Fire Emergency Response, Technology Acceptance, UTAUT, TOE Framework, Firefighters, Smart Emergency.

I. INTRODUCTION

The rapid evolution of digital technologies has transformed the operational landscape of emergency management and public safety services worldwide. Among these technologies, the Internet of Things (IoT) has emerged as a key enabler for enhancing communication efficiency, real-time monitoring, situational awareness, and operational coordination during emergencies [1][2]. IoT technologies integrate sensors, cloud computing, wireless communication, and smart devices to facilitate intelligent decision-making and automated emergency management systems [3].

Fire emergency response operations are highly dynamic and time-sensitive, requiring accurate information and rapid coordination among emergency personnel. Traditional emergency response systems often rely heavily on manual communication and human judgement, which may reduce operational effectiveness during critical incidents [4]. The implementation of IoT technologies can improve emergency response through automated fire detection, intelligent monitoring systems, wearable safety devices, and real-time command centre integration [5].

Globally, emergency organizations are increasingly adopting digital technologies as part of smart city and smart governance initiatives [6]. In Malaysia, the Malaysian Fire and Rescue Department (JBPM) has progressively integrated digital technologies into operational systems to improve public safety and emergency management efficiency. However, the successful implementation of IoT technologies depends significantly on users' acceptance, organizational readiness, technological infrastructure, and environmental support [7].

Technology acceptance theories such as the Unified Theory of Acceptance and Use of Technology (UTAUT) have been widely utilized to explain behavioural intention and user acceptance toward emerging technologies [3]. Similarly, the Technology–Organization–Environment

(TOE) framework emphasizes the importance of technological readiness, organizational support, and environmental influences in technology adoption [4]. Previous studies have applied these frameworks across various industries including healthcare, education, manufacturing, and public services [8][9]. Nevertheless, empirical studies specifically focusing on IoT acceptance within fire emergency response environments remain limited, particularly in developing countries.

Therefore, this study aims to investigate the determinants influencing IoT technology acceptance among Malaysian firefighters by integrating UTAUT and TOE perspectives. Specifically, the study examines the influence of Performance Expectancy, Effort Expectancy, Social Influence, Facilitating Conditions, Technological Context, Organizational Context, and Environmental Context on IoT acceptance among JBPM personnel.

II. LITERATURE REVIEW

A. Internet of Things (IoT) in Fire Emergency Response

The Internet of Things (IoT) refers to interconnected physical devices capable of collecting, exchanging, and analysing data through internet-based systems [10]. IoT technologies are increasingly utilized in emergency management due to their capability to provide real-time monitoring, predictive analytics, and automated communication [11].

In fire emergency response, IoT applications include smart fire detection systems, wearable sensors for firefighters, intelligent evacuation systems, drone surveillance, and integrated command centre operations [12]. These technologies enhance situational awareness and improve emergency coordination by enabling rapid information sharing among emergency personnel [13].

Recent studies indicate that IoT technologies can significantly improve firefighters' safety and operational effectiveness by reducing response time and supporting data-driven decision-making [14]. Furthermore, smart emergency systems are increasingly aligned with smart city initiatives and Industry 4.0 transformation agendas [15].

B. Unified Theory of Acceptance and Use of Technology (UTAUT)

The Unified Theory of Acceptance and Use of Technology (UTAUT) developed by Venkatesh *et al.* [16] is one of the most widely applied models for examining technology acceptance. The model includes four primary determinants: Performance Expectancy, Effort Expectancy, Social Influence, and Facilitating Conditions.

Performance Expectancy refers to the degree to which users believe technology improves job performance [16]. In emergency response settings, firefighters are more likely to adopt IoT technologies if they perceive improvements in operational efficiency, safety, and decision-making [17].

Effort Expectancy represents the perceived ease of technology use. Technologies with user-friendly interfaces and simplified operational procedures tend to achieve higher acceptance among emergency personnel [18].

Social Influence refers to the extent to which colleagues, supervisors, and organizational culture encourage technology adoption [16]. Facilitating Conditions involve the availability

of technical infrastructure, training, and organizational support necessary for successful technology implementation [19].

C. Technology–Organization–Environment (TOE) Framework

The Technology–Organization–Environment (TOE) framework developed by Tornatzky and Fleischer [20] explains organizational technology adoption from technological, organizational, and environmental perspectives.

The technological context refers to compatibility, reliability, scalability, and innovation capability of the technology [21]. Organizational context includes management support, organizational culture, financial resources, and employee readiness [22]. Environmental context focuses on external pressures such as government policies, industry standards, regulations, and societal expectations [23].

The integration of UTAUT and TOE provides a comprehensive framework for understanding technology acceptance in complex organizational environments such as emergency response agencies.

Based on the integration of the UTAUT and TOE frameworks, this study proposes a conceptual framework to examine the determinants influencing IoT technology acceptance among Malaysian firefighters. The framework combines individual, organizational, technological, and environmental factors that may influence firefighters' readiness and acceptance toward IoT implementation in emergency response operations.

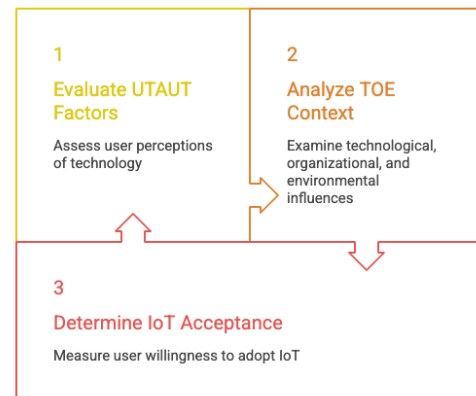


Figure 1. Proposed Integrated Research Framework.

Figure 1 illustrates the integrated conceptual framework combining the UTAUT and TOE models to examine determinants influencing IoT technology acceptance among Malaysian firefighters. The framework demonstrates how individual perceptions, organizational readiness, technological factors, and environmental influences collectively contribute toward IoT acceptance in fire emergency response operations.

III. METHODOLOGY

This study employed a quantitative research design using a structured questionnaire adapted from UTAUT and TOE constructs [16] [20]. The questionnaire consisted of demographic information and measurement items related to

Performance Expectancy, Effort Expectancy, Social Influence, Facilitating Conditions, Technological Context, Organizational Context, Environmental Context, and IoT Acceptance.

A total of 136 personnel from the Malaysian Fire and Rescue Department (JBPM) voluntarily participated in the survey using a convenience sampling approach. The respondents included operational officers, senior officers, and management personnel involved in emergency response operations. The majority of respondents possessed more than ten years of working experience in fire emergency management.

Table 1 Demographic Profile of Respondents

Demographic Variable	Category	Frequency (n)	Percentage (%)
Working Experience	Less than 2 years	7	5.1
	3–5 years	7	5.1
	6–8 years	15	11.0
	9–10 years	6	4.4
	More than 10 years	101	74.3
IoT Training Exposure	Yes	42	30.9
	No	94	69.1
Total Respondents		136	100

Most respondents possessed more than ten years of working experience in JBPM, indicating that the respondents were highly experienced personnel in fire emergency operations. Additionally, most respondents had not attended formal IoT training programmes, suggesting limited exposure to specialized digital technology training.

The questionnaire utilized a five-point Likert scale ranging from strongly disagree (1) to strongly agree (5). Data were analysed using Statistical Package for Social Sciences (SPSS) software. Descriptive statistics were conducted to determine respondents' perceptions toward IoT adoption, while one-way ANOVA analysis was performed to examine differences in acceptance levels based on working experience. Independent sample t-tests were also conducted to compare respondents with and without IoT training exposure.

IV. FINDINGS AND DISCUSSION

A. Descriptive Analysis

The findings indicate that respondents generally demonstrated positive perceptions toward IoT technology adoption in fire emergency response operations. All constructs recorded relatively high mean scores ranging from 3.57 to 4.08, indicating strong acceptance toward IoT implementation among JBPM personnel.

Performance Expectancy recorded a high mean score ($M = 4.08$), indicating that firefighters perceived IoT technologies as capable of enhancing operational efficiency and emergency decision-making. This finding is consistent

with previous UTAUT studies that identify perceived usefulness as a primary determinant of technology acceptance, suggesting that firefighters strongly believe IoT technologies can improve operational efficiency, tactical decision-making, and emergency response effectiveness. This finding is consistent with previous studies emphasizing the importance of perceived usefulness in technology acceptance [16] [17].

Organizational Context also recorded a high mean score (mean = 4.084), highlighting the critical role of management support, organizational readiness, and institutional commitment in facilitating technology adoption. This finding supports previous studies suggesting that organizational support significantly influences digital transformation success within public organizations [22].

Meanwhile, Facilitating Conditions recorded the lowest mean score (mean = 3.57), implying that technical infrastructure, training, and operational resources may still present implementation challenges. Similar challenges have been reported in previous emergency technology adoption studies [24].

Table 2 Descriptive Statistics of IoT Acceptance Constructs

Construct	Mean	Standard Deviation	Interpretation
Performance Expectancy (PE)	4.075	0.537	High
Effort Expectancy (EE)	4.000	0.541	High
Social Influence (SI)	4.046	0.561	High
Facilitating Conditions (FC)	3.572	0.874	Moderately High
Technological Context (TC)	3.957	0.651	High
Environmental Context (EC)	3.750	0.551	High
Organizational Context (OC)	4.084	0.582	High
IoT Acceptance (IA)	4.039	0.734	High

Table 2 presents the descriptive statistics of the IoT acceptance constructs among JBPM personnel. The findings indicate that all constructs recorded relatively high mean scores ranging from 3.57 to 4.08, demonstrating positive perceptions toward IoT implementation in fire emergency response operations.

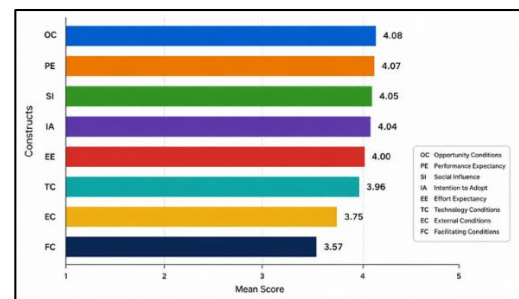


Figure 2. Comparison of Mean Scores Across UTAUT and TOE Constructs Influencing IoT Technology Acceptance among Malaysian Firefighters.

Figure 2 illustrates the comparative mean scores of the investigated constructs influencing IoT technology acceptance among Malaysian firefighters. Organizational Context (OC) recorded the highest mean score (4.08), followed closely by Performance Expectancy (PE) (4.07), indicating that organizational support and perceived operational benefits are the most influential factors affecting IoT acceptance. Social Influence (SI) and IoT Acceptance (IA) also demonstrated high mean values, reflecting positive perceptions toward IoT integration within fire emergency response operations. In contrast, Facilitating Conditions (FC) recorded the lowest mean score (3.57), suggesting potential challenges related to technical infrastructure, operational support, and resource availability for IoT implementation within emergency response environments.

B. ANOVA Analysis Based on Working Experience

The ANOVA findings revealed significant differences between working experience groups for IoT Acceptance, Performance Expectancy, Social Influence, and Technological Context. This indicates that operational experience significantly influences firefighters' perceptions and acceptance toward IoT technologies.

Experienced firefighters may possess stronger operational awareness and greater appreciation of how IoT technologies can improve emergency coordination, situational awareness, and firefighter safety. Their exposure to real emergency incidents may strengthen their confidence in utilizing advanced technologies during critical operations [25].

Interestingly, Environmental Context was found to be nearly significant, suggesting that government policies, international standards, and societal expectations may also influence IoT adoption within emergency organizations.

Table 3 ANOVA Analysis Based on Working Experience

Construct	F-value	p-value	Significance
IoT Acceptance (IA)	6.226	0.0001	Significant
Performance Expectancy (PE)	2.692	0.0338	Significant
Effort Expectancy (EE)	1.237	0.299	Not Significant
Facilitating Conditions (FC)	1.965	0.104	Not Significant
Organizational Context (OC)	1.777	0.137	Not Significant
Environmental Context (EC)	2.358	0.0568	Nearly Significant
Social Influence (SI)	3.043	0.0195	Significant
Technological Context (TC)	2.804	0.0284	Significant

The ANOVA results revealed that working experience significantly influenced IoT Acceptance, Performance Expectancy, Social Influence, and Technological Context. This suggests that experienced firefighters demonstrate stronger acceptance and understanding of IoT technologies in emergency response operations.

C. IoT Training Exposure

The findings showed no significant differences between respondents who attended IoT training and those without training exposure. This finding suggests that generalized ICT training alone may not sufficiently influence technology acceptance among firefighters.

One possible explanation is that existing training programmes may focus more on general digital competencies rather than operational IoT applications specifically related to emergency response. Another explanation is that real operational experience contributes more substantially toward technology acceptance than conventional classroom-based IoT training.

This finding represents an important contribution to the literature because it highlights the importance of operational exposure and experiential learning in shaping technology acceptance among emergency personnel. Therefore, future training programmes should incorporate simulation-based learning, scenario-based operational exercises, and practical IoT integration approaches to improve technology readiness among firefighters.

Table 4 Independent Sample t-Test Based on IoT Training Exposure

Construct	Mean (Training = Yes)	Mean (Training = No)	p-value	Interpretation
IoT Acceptance (IA)	3.895	4.103	0.142	Not Significant
Performance Expectancy (PE)	3.955	4.111	0.282	Not Significant
Effort Expectancy (EE)	3.981	4.009	0.800	Not Significant
Facilitating Conditions (FC)	3.481	3.613	0.440	Not Significant
Organizational Context (OC)	4.014	4.115	0.402	Not Significant
Environmental Context (EC)	3.695	3.775	0.416	Not Significant
Social Influence (SI)	3.990	4.070	0.459	Not Significant
Technological Context (TC)	3.905	3.981	0.541	Not Significant

Interestingly, respondents without formal IoT training consistently recorded slightly higher mean scores than those who had attended training programmes, although these differences were not statistically significant. One possible explanation is that experienced firefighters may develop favourable perceptions of IoT technologies through extensive operational exposure rather than formal classroom training. Another possibility is that existing training programmes focus on general ICT knowledge instead of practical IoT applications for emergency response. Consequently, participants who completed the training may possess a more realistic understanding of current technological limitations, resulting in more conservative evaluations. This finding highlights the need to redesign IoT training by incorporating simulation-based exercises and operational scenarios that better reflect real emergency response environments.

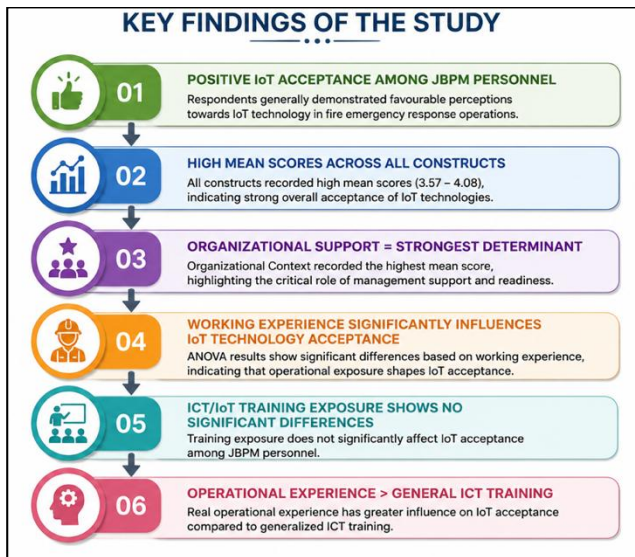


Figure 3. Key Findings of the Study.

Figure 3 summarizes the major findings of the study. The results indicate that firefighters generally demonstrated positive acceptance toward IoT implementation in emergency response operations. Organizational support emerged as the strongest determinant influencing IoT acceptance, while working experience significantly affected technology acceptance levels. Interestingly, IoT training exposure did not produce significant differences, suggesting that operational experience may have greater influence on technology acceptance than generalized IoT training programmes.

Despite the positive acceptance of IoT technologies, several implementation challenges remain. Emergency response agencies require reliable digital infrastructure, interoperability between legacy and IoT-based systems, cybersecurity protection, continuous maintenance, and sufficient funding for large-scale deployment. Moreover, operational personnel require scenario-based training that reflects real emergency environments rather than conventional classroom instruction. These practical considerations should be addressed before nationwide implementation of IoT-enabled fire emergency systems.

V. CONCLUSION

This study investigated the determinants of IoT technology acceptance among Malaysian firefighters using an integrated UTAUT and TOE perspective. The findings demonstrated positive acceptance toward IoT implementation in fire emergency response operations, with Performance Expectancy and Organizational Context emerging as the strongest determinants influencing acceptance.

The study further revealed that working experience significantly influences IoT acceptance, while ICT/IoT training exposure does not produce significant differences. These findings suggest that operational experience may play a more important role in shaping technology acceptance compared to generalized ICT training programmes.

This study contributes empirical evidence toward the growing body of literature on smart emergency systems and digital transformation within emergency response

organizations. Practically, the findings provide valuable insights for policymakers, emergency agencies, and technology developers in designing more effective IoT implementation strategies for next-generation fire emergency response systems.

Future studies should employ Structural Equation Modelling (SEM) or Partial Least Squares SEM (PLS-SEM) to validate the causal relationships among UTAUT and TOE constructs. Such analyses would provide stronger theoretical validation by simultaneously examining measurement reliability and structural relationships among latent variables.

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REFERENCES

- [1] L. Da Xu, W. He, and S. Li, "Internet of Things in Industries: A Survey," *IEEE Trans. Industr. Inform.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014, doi: 10.1109/TII.2014.2300753.
- [2] H. Boyes, B. Hallaq, J. Cunningham, and T. Watson, "The industrial internet of things (IIoT): An analysis framework," *Comput. Ind.*, vol. 101, pp. 1–12, Oct. 2018, doi: 10.1016/j.compind.2018.04.015.
- [3] Kevin Ashton, "That 'Internet of Things' Thing," *RFID Journal*, 2009.
- [4] J. Weidinger, S. Schlauderer, and S. Overhage, "Determinants for the acceptance of emergency response information systems: Ethnographical insights into the digitalization of a voluntary fire department," *International Journal of Disaster Risk Reduction*, vol. 109, p. 104603, Jul. 2024, doi: 10.1016/j.ijdr.2024.104603.
- [5] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Computer Networks*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010, doi: 10.1016/j.comnet.2010.05.010.
- [6] A. Caragliu, C. Del Bo, and P. Nijkamp, "Smart Cities in Europe," *Journal of Urban Technology*, vol. 18, no. 2, pp. 65–82, Apr. 2011, doi: 10.1080/10630732.2011.601117.
- [7] D. Marikyan, S. Papagiannidis, and E. Alamanos, "Smart Home Technology Acceptance: An Empirical Investigation," 2019, pp. 305–315. doi: 10.1007/978-3-030-29374-1_25.
- [8] F. D. Davis, "Perceived usefulness, perceived ease of use, and user acceptance of information technology," *MIS Q.*, vol. 13, no. 3, pp. 319–339, 1989, doi: 10.2307/249008.
- [9] I. Ajzen, "The theory of planned behavior," *Organ. Behav. Hum. Decis. Process.*, vol. 50, no. 2, pp. 179–211, 1991.
- [10] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Generation Computer Systems*, vol. 29, no. 7, pp. 1645–1660, Sep. 2013, doi: 10.1016/j.future.2013.01.010.
- [11] S. Madakam, R. Ramaswamy, and S. Tripathi, "Internet of Things (IoT): A Literature Review," *Journal of Computer and Communications*, vol. 03, no. 05, pp. 164–173, 2015, doi: 10.4236/jcc.2015.35021.
- [12] A. K. Singh, N. Firoz, A. Tripathi, K. K. Singh, P. Choudhary, and P. C. Vashist, "Internet of Things: from hype to reality," in *An Industrial IoT Approach for Pharmaceutical Industry Growth*, Elsevier, 2020, pp. 191–230. doi: 10.1016/B978-0-12-821326-1.00007-3.

- [13] R. Khan, S. U. Khan, R. Zaheer, and S. Khan, "Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges," in 2012 10th International Conference on Frontiers of Information Technology, IEEE, Dec. 2012, pp. 257–260. doi: 10.1109/FIT.2012.53.
- [14] Z. Boboyeva, R. Sokhibov, I. Yuldashev, and A. Ma'murov, "A Survey on Internet of things architectures," E3S Web of Conferences, vol. 402, p. 03053, Jul. 2023, doi: 10.1051/e3sconf/202340203053.
- [15] L. Monostori, "Cyber-physical Production Systems: Roots, Expectations and R&D Challenges," Procedia CIRP, vol. 17, pp. 9–13, 2014, doi: 10.1016/j.procir.2014.03.115.
- [16] V. Venkatesh, M. G. Morris, G. B. Davis, and F. D. Davis, "User Acceptance of Information Technology: Toward a Unified View," 2003.
- [17] Y. K. Dwivedi, M. A. Shareef, A. C. Simintiras, B. Lal, and V. Weerakkody, "A generalised adoption model for services: A cross-country comparison of mobile health (m-health)," Gov. Inf. Q., vol. 33, no. 1, pp. 174–187, Jan. 2016, doi: 10.1016/j.giq.2015.06.003.
- [18] M. Fishbein and I. Ajzen, Predicting and Changing Behavior. Psychology Press, 2011. doi: 10.4324/9780203838020.
- [19] T. Oliveira and Maria F. O. Martins, "Literature Review of Information Technology Adoption Models at Firm Level," Computer Science, Business, Economics, 2011.
- [20] Louis G. Tornatzky, Mitchell Fleischer, and Alok K. Chakrabarti, The Processes of Technological Innovation. Lexington Books, 1990.
- [21] J. Baker, "The Technology–Organization–Environment Framework," 2012, pp. 231–245. doi: 10.1007/978-1-4419-6108-2_12.
- [22] C. Low, Y. Chen, and M. Wu, "Understanding the determinants of cloud computing adoption," Industrial Management & Data Systems, vol. 111, no. 7, pp. 1006–1023, Aug. 2011, doi: 10.1108/02635571111161262.
- [23] H. Gangwar, H. Date, and R. Ramaswamy, "Understanding determinants of cloud computing adoption using an integrated TAM-TOE model," Journal of Enterprise Information Management, vol. 28, no. 1, pp. 107–130, Feb. 2015, doi: 10.1108/JEIM-08-2013-0065.
- [24] B. N. Schilit and M. M. Theimer, "Disseminating active map information to mobile hosts," IEEE Netw., vol. 8, no. 5, pp. 22–32, Sep. 1994, doi: 10.1109/65.313011.
- [25] A. Parasuraman, "Technology Readiness Index (Tri)," J. Serv. Res., vol. 2, no. 4, pp. 307–320, May 2000, doi: 10.1177/109467050024001.

Development and Performance Evaluation of an IoT-Based Emergency Alert System for Real-Time Occupational Safety and Disaster Response in Industrial Facilities

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ABSTRACT — Industrial facilities are exposed to various occupational hazards that require rapid and reliable emergency response mechanisms. Conventional emergency reporting methods, such as telephone calls and radio communication, often experience delays that can increase the severity of workplace accidents and hinder effective rescue operations. This study presents the development and performance evaluation of an Internet of Things (IoT)-based emergency alert system designed for real-time occupational safety and disaster response in industrial environments. The proposed system integrates ESP8266 NodeMCU microcontrollers, emergency push-button devices, Wi-Fi communication networks, Firebase Realtime Database, and Android-based mobile applications to facilitate immediate emergency notification delivery. The system architecture enables workers to trigger emergency alerts that are transmitted through cloud services and received instantly by Occupational Safety and Health (OSH) personnel. Experimental testing was conducted under simulated industrial conditions to evaluate notification delay, communication reliability, power consumption, network stability, and system responsiveness. Results indicate an average notification delay of 2.3 seconds with a communication reliability of 98%. The system consumed only 0.9 W of power and maintained network connectivity stability above 97% during a 60-minute observation period. Comparative analysis demonstrates that the proposed IoT-based solution significantly outperforms conventional emergency communication methods in terms of response time, accessibility, scalability, and real-time monitoring capability. The findings confirm that the developed system provides a low-cost, reliable, and scalable approach for enhancing occupational safety management and emergency response effectiveness in industrial facilities. Furthermore, the proposed architecture supports Industry 4.0 initiatives by leveraging connectivity, cloud computing, and intelligent communication technologies to improve workplace safety and operational resilience.

KEYWORDS: Internet of Things, Occupational Safety, Emergency Alert System, ESP8266, Industrial Safety, Industry 4.0, Real-Time Monitoring.

I. INTRODUCTION

Industrial sectors remain among the most hazardous workplaces worldwide. According to the International Labour Organization (ILO), approximately 2.78 million workers die annually due to occupational accidents and work-related diseases. Furthermore, hundreds of millions of non-fatal workplace injuries occur each year, causing significant economic losses, reduced productivity, and adverse social consequences for workers and their families[1]. The increasing complexity of industrial processes, combined with the widespread use of heavy machinery, hazardous materials, and automated production systems, has further heightened the importance of effective occupational safety management.

Industrial facilities such as steel manufacturing plants, boiler fabrication workshops, chemical processing industries, mining operations, and large-scale construction projects are characterized by numerous occupational hazards[2]. These hazards include mechanical failures, equipment malfunctions, fire outbreaks, explosions, chemical spills, electrical accidents, and environmental disasters. In many cases, the severity of an accident is directly influenced by the speed and effectiveness of the emergency response process. Therefore, rapid communication between workers, supervisors, and Occupational Health and Safety (OSH) personnel is essential to minimize injuries, prevent fatalities, and reduce property damage[3].

Despite significant advancements in industrial safety practices, many organizations still rely on conventional emergency reporting mechanisms such as telephone calls, handheld radios, manual alarms, or direct verbal communication. While these methods remain widely used, they often suffer from several limitations, including delayed reporting, communication breakdowns, human error, and limited accessibility during emergency situations[4].

The rapid evolution of digital technologies and the emergence of Industry 4.0 have created new opportunities for improving workplace safety through intelligent

monitoring and communication systems. Among these technologies, the Internet of Things (IoT) has attracted considerable attention due to its ability to interconnect physical devices, sensors, controllers, and cloud computing platforms through internet-based communication networks[5], [6]. IoT enables real-time data acquisition, remote monitoring, predictive analysis, and automated decision-making, making it a promising solution for industrial safety applications.

Several studies have demonstrated the effectiveness of IoT technologies in enhancing industrial operations, including predictive maintenance, environmental monitoring, worker tracking, and hazard detection systems [7], [8]. In occupational safety applications, IoT-based solutions can facilitate continuous monitoring of workplace conditions, automatic incident detection, and rapid notification of emergency events. By integrating sensors, wireless communication modules, cloud databases, and mobile applications, organizations can establish intelligent safety ecosystems capable of improving situational awareness and accelerating emergency response procedures.

In addition, the increasing availability of low-cost microcontrollers such as ESP8266 and ESP32[9], coupled with cloud-based platforms and smartphone technologies, has significantly reduced the implementation cost of IoT systems. These technological advancements provide industries with practical opportunities to deploy scalable and cost-effective safety solutions without requiring extensive infrastructure investments. As a result, IoT-based emergency communication systems are becoming increasingly attractive for small, medium, and large industrial enterprises.

Emergency alert systems represent one of the most critical components of modern occupational safety management. An effective emergency alert system should provide immediate notification, accurate incident information, reliable communication channels, and accessibility for both workers and emergency responders. Furthermore, the system must maintain operational reliability under various environmental and network conditions commonly encountered in industrial facilities. Therefore, evaluating system performance, including notification latency, communication reliability, and operational stability, is essential before large-scale deployment.

This research develops and evaluates an IoT-based emergency alert system designed specifically for occupational accident and disaster reporting in industrial facilities. The proposed system utilizes ESP8266 NodeMCU microcontrollers, emergency push-button devices[10], Wi-Fi communication networks, cloud-based databases, and Android mobile applications to facilitate real-time emergency notifications. When activated, the emergency button instantly transmits incident information to designated safety personnel through internet-connected devices, enabling rapid response and improved coordination during emergency situations.

The main contributions of this study are threefold. First, it proposes a practical and low-cost IoT architecture for industrial emergency communication. Second, it implements a real-time notification mechanism capable of delivering emergency alerts to safety officers within seconds. Third, it evaluates the system's performance based on notification delay, communication reliability, and operational effectiveness under industrial conditions. The findings are expected to contribute to the development of smart occupational safety systems and support the broader adoption of Industry 4.0 technologies in workplace safety management.

The remainder of this paper is organized as follows. Section II presents the literature review related to IoT technologies and emergency communication systems. Section III describes the proposed system architecture and research methodology. Section IV discusses the experimental results and performance evaluation. Finally, Section V concludes the paper and outlines potential directions for future research.

II. LITERATURE REVIEW

A. *Internet of Things in Industrial Safety*

The Internet of Things (IoT) has emerged as one of the most transformative technologies in the era of Industry 4.0. IoT refers to a network of interconnected physical devices embedded with sensors, actuators, communication modules, and computational capabilities that enable them to collect, exchange, and process data through internet-based infrastructures [11], [12], [13]. The integration of IoT technologies facilitates seamless communication between physical assets and digital platforms, allowing real-time monitoring, control, and intelligent decision-making across various application domains [14], [15]. By continuously collecting operational data from distributed devices, organizations can improve situational awareness and proactively address potential risks before they escalate into serious incidents [14], [16], [17], [18], [19].

B. *Occupational Safety Management Systems*

Occupational Safety and Health (OSH) management systems are designed to identify, assess, control, and continuously improve workplace safety performance. The primary objective of OSH management is to minimize occupational risks, prevent workplace injuries, and create safe working environments for employees [20]. International standards such as ISO 45001 emphasize the importance of systematic risk management, incident reporting, hazard identification, and continuous improvement in safety practices [21], [22], [23].

The digital transformation of industrial operations has led to the integration of advanced information technologies into occupational safety management systems. Modern safety platforms increasingly utilize sensors, wireless communication networks, cloud services, and mobile applications to support real-time hazard detection and incident reporting[24], [25], [26]. In addition, digital reporting systems enhance the accuracy and traceability of

safety records, facilitating incident investigations and regulatory compliance, [27].

C. Emergency Alert Systems

Emergency alert systems are critical components of modern industrial safety infrastructures. These systems are designed to provide immediate communication and notification regarding hazardous events, enabling rapid response and effective coordination among workers, safety personnel, and emergency responders [28], [29], [30]. The growing availability of wireless communication technologies has encouraged researchers to develop digital emergency notification systems capable of providing real-time information delivery [31]. Similarly, Handoko *et al.* [32] implemented a LoRa and GPS-based emergency communication system for mountain rescue operations [33], [34]. Such capabilities are particularly beneficial in industrial environments where safety officers may be responsible for monitoring multiple operational areas simultaneously [35], [36], [37].

III. METHODOLOGY

A. Research Method

This study adopts a design and experimental research approach to develop and evaluate an Internet of Things (IoT)-based emergency alert system for occupational safety and disaster response in industrial facilities. The research methodology consists of four main stages: system requirement analysis, hardware and software development, system implementation, and performance evaluation.

The requirement analysis stage identifies operational challenges associated with conventional emergency reporting mechanisms commonly used in industrial environments. Based on these findings, a low-cost and real-time emergency communication architecture was designed to facilitate rapid incident reporting between workers and Occupational Safety and Health (OSH) personnel.

The development phase involves the integration of embedded hardware, wireless communication technologies, cloud computing platforms, and mobile applications. Following system implementation, experimental testing was conducted to evaluate communication latency, reliability, system responsiveness, and operational stability under various network conditions. The overall research framework is illustrated in Figure 1, consisting of system design, implementation, testing, and performance evaluation stages.

B. System Architecture

The proposed emergency alert system follows a cloud-connected IoT architecture that enables real-time communication between industrial workers and safety officers. The architecture consists of three primary layers:

1. Sensing and Data Acquisition Layer
2. Communication and Cloud Layer
3. Application and User Interface Layer

The sensing layer comprises emergency button devices equipped with ESP8266 NodeMCU microcontrollers.

The system workflow can be mathematically represented as:

$$T_{total} = T_{detect} + T_{transmit} + T_{cloud} + T_{notify} \quad (1)$$

where:

- T_{total} = Total notification delay
- T_{detect} = Button detection time
- $T_{transmit}$ = Data transmission time
- T_{cloud} = Cloud processing time
- T_{notify} = Mobile notification delivery time

The primary performance objective is minimizing T_{total} to improve emergency response effectiveness [37], [38].

D. Hardware Design

The emergency alert unit was designed using low-cost and commercially available components to ensure practical implementation in industrial environments.

Table 1 Hardware Configuration

Component	Function
ESP8266 NodeMCU	Main controller and IoT communication module
Push Button	Emergency trigger device
LED Indicator	System status visualization
Buzzer	Local audible alarm
Power Supply	Electrical power source
Wi-Fi Network	Wireless communication medium

The ESP8266 NodeMCU was selected due to its integrated Wi-Fi capability, low power consumption, and suitability for IoT applications. The microcontroller continuously monitors the emergency button state and executes predefined communication protocols when activation occurs.

The push button serves as the primary emergency input device. Upon activation, the system immediately generates an emergency event and initiates cloud communication.

The LED indicator provides visual feedback regarding system operational status, including power availability, Wi-Fi connectivity, and successful data transmission.

The buzzer generates local audible alerts to notify nearby workers and supervisors of emergency conditions before external responders arrive.

E. Software Design

The software architecture consists of embedded firmware running on the ESP8266 microcontroller and a cloud-based notification platform connected to an Android application. The firmware was developed using the Arduino IDE programming environment and programmed in C++.

The main software functions include:

1. Wi-Fi connection establishment
2. Button state monitoring
3. Emergency event generation
4. Firebase database communication

5. Cloud synchronization
6. Notification transmission
7. System status monitoring
8. Error handling and reconnection procedures

F. Performance Evaluation

To assess system effectiveness, several performance parameters were measured during experimental testing. Notification Delay

Notification delay represents the time interval between emergency button activation and notification reception on the Android device.

$$Delay = T_{receive} - T_{press} \quad (2)$$

Reliability

Communication reliability is calculated as:

$$Reliability(\%) = \frac{N_{success}}{N_{total}} \times 100 \quad (3)$$

where:

1. $N_{success}$ = Successful notifications
2. N_{total} = Total transmitted notifications

Power Consumption

Power consumption is evaluated using:

$$P = V \times I \quad (4)$$

where:

1. P = Power (W)
2. V = Voltage (V)
3. I = Current (A)

These performance indicators provide quantitative measurements of system efficiency and suitability for industrial deployment.

IV. EXPERIMENTAL SETUP

A. Experimental Environment

To evaluate the effectiveness and operational performance of the proposed IoT-based emergency alert system, a series of experimental tests were conducted in a simulated industrial environment. The testing environment was designed to represent actual workplace conditions commonly found in manufacturing facilities, steel processing plants, fabrication workshops, and other industrial settings where rapid emergency communication is critical.

The experimental setup consisted of an emergency alert unit equipped with an ESP8266 NodeMCU microcontroller, emergency push button, LED indicator, buzzer alarm, and Wi-Fi communication module. The emergency unit was connected to a Firebase Realtime Database through a wireless internet connection. An Android-based mobile application was installed on safety personnel smartphones to receive emergency notifications generated by the system.

The testing scenario was designed to emulate workplace accident situations where immediate communication between workers and Occupational Safety and Health (OSH) personnel is required. Examples of simulated incidents included machinery-related accidents, fire emergencies, electrical faults, and hazardous environmental conditions.

A schematic representation of the experimental setup is shown in Figure 1.

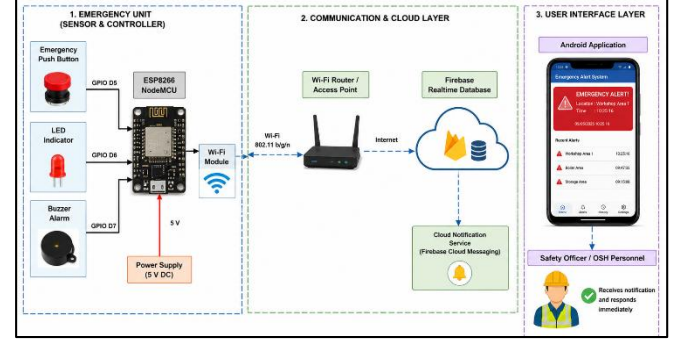


Figure 1. shows a schematic representation of the experimental setup.

This architecture enables end-to-end communication between workers and emergency responders through a real-time IoT infrastructure.

B. Experimental Procedure

The evaluation process was conducted through repeated testing sessions to ensure statistical consistency and measurement reliability.

C. Performance Evaluation Parameters

1. Notification Delay

Notification delay represents the elapsed time between emergency button activation and successful notification reception on the Android device.

Rapid notification delivery is essential because delayed communication can significantly increase accident severity and response time. Therefore, minimizing notification latency is one of the primary objectives of the proposed system.

The notification delay is calculated as:

$$T_d = T_r - T_p \quad (4)$$

where:

- T_d = Notification delay (s)
- T_r = Notification reception time (s)
- T_p = Emergency button activation time (s)

The average delay value is determined using:

$$\bar{T}_d = \frac{\sum_{i=1}^n T_{d_i}}{n} \quad (5)$$

where:

n = Number of experiments

- 1) Lower delay values indicate better system responsiveness.

2. Data Transmission Reliability

Communication reliability refers to the system's ability to successfully transmit emergency notifications without packet loss or transmission failure. Reliability is one of the most important performance indicators for safety-critical applications because missed notifications may prevent emergency responders from receiving incident information. Reliability is calculated as:

$$R = \frac{N_s}{N_t} \times 100\% \quad (6)$$

A reliability value greater than 95% is generally considered acceptable for industrial emergency communication systems.

3. Power Consumption

Power efficiency is evaluated to determine the feasibility of long-term deployment and potential battery-operated operation.

Power consumption is calculated using:

$$P = V \times I \quad (7)$$

Measurements were conducted during both standby and emergency transmission modes to analyze energy requirements under different operating conditions. Low power consumption is desirable because it improves system sustainability and reduces operational costs.

4. Network Connectivity Stability

Since the proposed system relies on wireless communication, network stability plays a critical role in ensuring reliable emergency notification delivery.

Network connectivity stability was evaluated by continuously monitoring:

1. Wi-Fi connection availability
2. Reconnection capability
3. Packet transmission success
4. Cloud synchronization consistency

The stability percentage was calculated using:

$$S = \frac{T_c}{T_o} \times 100\% \quad (8)$$

Stable network performance is essential for maintaining uninterrupted emergency communication.

5. System Responsiveness

System responsiveness represents the ability of the emergency alert device to detect an emergency events and initiate communication processes immediately after button activation.

The response time includes:

1. Button detection time
2. Microcontroller processing time
3. Data packet generation time
4. Network initialization time

The total system response time is expressed as:

$$T_s = T_b + T_p + T_t \quad (9)$$

High responsiveness is crucial for reducing overall emergency notification latency.

D. Testing Scenarios

To simulate realistic industrial operating conditions, three testing scenarios were performed.

Scenario 1: Normal Network Condition

The emergency alert system operated under stable Wi-Fi connectivity with minimal network congestion.

Objective:

1. Measure baseline system performance.
2. Determine average notification delay.

Scenario 2: Moderate Network Traffic

The system was tested while multiple devices simultaneously accessed the wireless network.

Objective:

1. Evaluate communication robustness.
2. Analyze delay variations under network load.

Scenario 3: Intermittent Connectivity

The Wi-Fi connection was intentionally disrupted to assess system recovery and reconnection capabilities.

Objective:

1. Evaluate fault tolerance.
2. Measure reconnection performance.
3. Assess notification reliability under unstable network conditions.

Statistical analysis provides a quantitative basis for evaluating system performance and identifying potential limitations of the proposed emergency communication platform.

V. RESULTS AND DISCUSSION

A. Notification Delay Analysis

Notification latency is one of the most critical performance indicators in emergency communication systems because it directly influences response effectiveness during accident and disaster situations. To evaluate the responsiveness of the proposed IoT-based emergency alert system, ten experimental trials were conducted under stable Wi-Fi network conditions.



Figure 2. Experimental Prototype of the Multi-Zone IoT-Based Emergency Alert System Consisting of Two Monitoring Zones (Zone-1 and Zone-2) Using ESP8266 NodeMCU Controllers.

Figure 2 presents the developed hardware prototype of the IoT-based emergency alert system. The prototype consists of two monitoring zones equipped with ESP8266 NodeMCU microcontrollers, emergency push buttons, LED indicators, and buzzer alarms. Each zone is configured to simulate emergency reporting from different industrial locations. The devices communicate through a Wi-Fi network and transmit emergency data to a cloud server for real-time monitoring and notification delivery to Occupational Safety and Health (OSH) personnel. The experimental setup was utilized to evaluate notification delay, communication reliability, and overall system responsiveness under simulated industrial emergency conditions.

The delay was measured as the time interval between emergency button activation and notification reception on the Android application used by Occupational Safety and Health (OSH) personnel.

Table 2 Notification Delay Measurements

Trial	Delay (s)
1	2.1
2	2.4
3	2.2
4	2.5
5	2.3
6	2.1
7	2.4
8	2.2
9	2.3
10	2.5

The average notification delay was calculated as:

$$\bar{T}_d = \frac{\sum_{i=1}^{10} T_i}{10}$$

$$\bar{T}_d = 2.3 \text{ seconds}$$

To further evaluate system consistency, the standard deviation was calculated:

$$\sigma = 0.15 \text{ seconds}$$

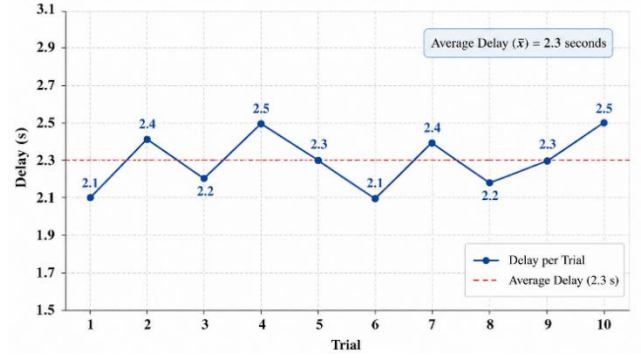


Figure 3. Notification Delay Measurements.

B. Reliability Evaluation

Reliability is a fundamental requirement for safety-critical systems because communication failures may result in delayed responses and increased accident severity. To evaluate communication reliability, 100 emergency alert transmissions were generated under normal operating conditions. Each transmission was monitored to determine whether the notification was successfully delivered to the Android application.

Table 3 Reliability Test Results

Parameter	Result
Total Alerts	100
Successful Alerts	98
Failed Alerts	2
Reliability	98%

System reliability was calculated using:

$$R = \frac{N_s}{N_t} \times 100\%$$

where:

$$N_s = 98$$

$$N_t = 100$$

Thus:

$$R = 98\%$$

C. Power Consumption Analysis

Energy efficiency is an important consideration in IoT-based systems because emergency devices are often required to operate continuously for extended periods. Power consumption measurements were conducted using a digital power analyzer while the system operated under normal monitoring conditions.

Table 4 Power Consumption Measurements

Parameter	Value
Voltage	5 V
Current	0.18 A
Power	0.9 W

Power consumption was calculated as:

$$P = V \times I$$

$$P = 5 \times 0.18$$

$$P = 0.9W$$

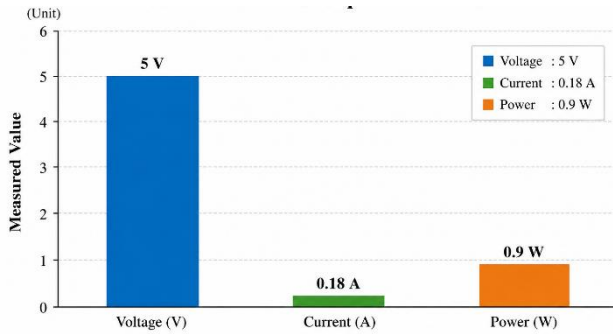


Figure 4. Measured Voltage, Current and Power consumption.

The measured power requirement of 0.9 W indicates highly efficient operation. Assuming continuous operation for 24 hours, the daily energy consumption can be estimated as:

$$E = P \times t$$

$$E = 0.9 \times 24$$

$$E = 21.6Wh/day$$

D. Network Connectivity Stability

Network connectivity plays a crucial role in determining the effectiveness of IoT-based emergency communication systems. To evaluate communication stability, the system was monitored continuously during operation under varying network conditions. The Wi-Fi connection maintained a stable communication link throughout most of the testing period, achieving an average connectivity stability exceeding 97%.

The findings are consistent with previous studies reporting the effectiveness of Wi-Fi-based IoT communication platforms for industrial monitoring applications [40].

Table 5. Wi-Fi Network Connectivity Stability During 60 Minutes

Time (min)	Stability (%)
0	100.0
5	99.5
10	99.0
15	97.8
20	97.2
25	98.3
30	98.2
35	98.5
40	97.4
45	98.7
50	98.6
55	98.9
60	98.4

The network connectivity stability of the proposed IoT-based emergency alert system was evaluated continuously over a 60-minute observation period.

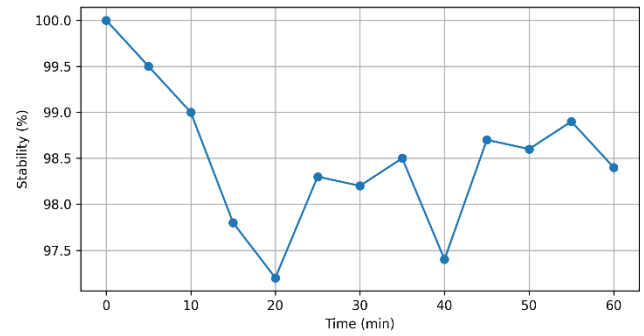


Figure 5. Wi-Fi Network Connectivity Stability During 60 Minutes.

E. System Responsiveness

System responsiveness refers to the capability of the emergency device to detect and process emergency events immediately after button activation.

The total notification delay can be represented as the sum of the following components:

$$T_{total} = T_{detect} + T_{process} + T_{transmit} + T_{notify}$$

Table 6. Comparison Between Conventional and Proposed Systems

Feature	Conventional System	Proposed IoT System
Notification Method	Telephone/Radio	Mobile Notification
Response Time	Several Minutes	Approximately 2.3 s
Coverage	Limited	Internet-Based
Data Logging	Manual	Automatic
Scalability	Low	High
Real-Time Monitoring	No	Yes

Unlike conventional approaches that depend heavily on human intervention, the proposed system automates the entire emergency communication process.

VI. CONCLUSION

This study developed and evaluated an IoT-based emergency alert system for real-time occupational safety applications in industrial facilities using ESP8266 NodeMCU, Wi-Fi communication, Firebase Realtime Database, and an Android mobile application. Experimental results demonstrated an average notification delay of 2.3 s, communication reliability of 98%, power consumption of only 0.9 W, and network connectivity stability above 97%, indicating that the system provides reliable and efficient emergency communication.

Compared with conventional reporting methods, the proposed system enables faster notification, automated data logging, broader communication coverage, and real-time monitoring, thereby improving emergency response coordination and workplace safety management. The proposed architecture also supports Industry 4.0 implementation through cloud-based connectivity and digital communication.

Future work will focus on integrating additional environmental sensors, GPS-based localization, and artificial intelligence techniques to enable automatic hazard detection and predictive safety management in industrial environments.

REFERENCES

- [1] J. P. Luna, C. V. Naccha, K. T. Chuquiruna, O. C. Boza, and C. B. Mejia, "The Role of Epistemology in Engineering-Based Occupational Health and Safety Management Systems," *Pak. J. Life Soc. Sci.*, vol. 22, no. 2, 2024, doi: 10.57239/PJLSS-2024-22.2.00589.
- [2] J. Prata, C. L. Simões, and R. Simoes, "Improvements to Municipal Solid Waste Collection Systems Using Real-Time Monitoring," *Sustainability (Switzerland)*, vol. 17, no. 4, 2025, doi: 10.3390/su17041405.
- [3] D. Daraba, F. Pop, and C. Daraba, "Digital Twin Used in Real-Time Monitoring of Operations Performed on CNC Technological Equipment," *Applied Sciences (Switzerland)*, vol. 14, no. 22, 2024, doi: 10.3390/app142210088.
- [4] Z. Ye *et al.*, "IoT-enhanced smart road infrastructure systems for comprehensive real-time monitoring," *Internet of Things and Cyber-Physical Systems*, vol. 4, 2024, doi: 10.1016/j.iotcps.2024.01.002.
- [5] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Computer Networks*, 54(15), 2787–2805. <https://doi.org/10.1016/j.comnet.2010.05.010>, *Computer Networks*, vol. 54, no. 15, 2010.
- [6] A. S. Rao *et al.*, "Real-time monitoring of construction sites: Sensors, methods, and applications," 2022. doi: 10.1016/j.autcon.2021.104099.
- [7] D. X. L., H. W., and L. S., "Internet of Things in Industries: A Survey," *IEEE Trans. Industr. Inform.*, vol. 10, no. 4, 2014.
- [8] Y. S. Parihar, "Internet of Things and Nodemcu A review of use of Nodemcu ESP8266 in IoT products," *Journal of Emerging Technologies and Innovative Research (JETIR)*, vol. 6, no. 6, 2019.
- [9] Hanan, A. A. N. Gunawan, and M. Sumadiyasa, "Water level detection system based on ultrasonic sensors HC-SR04 and Esp8266-12 modules with telegram and buzzer communication media," *Instrumentation Mesure Metrologie*, vol. 18, no. 3, 2019, doi: 10.18280/i2m.180311.
- [10] L. Santos, T. Costa, J. M. L. P. Caldeira, and V. N. G. J. Soares, "Performance Assessment of ESP8266 Wireless Mesh Networks," *Information (Switzerland)*, vol. 13, no. 5, 2022, doi: 10.3390/info13050210.
- [11] A. Al-Fuqaha, "AL-FA-Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," *IEEE Communication Surveys & Tutorials (Accepted for publication)*, vol. 1, no. 2, 2013.
- [12] M. Aledhari, R. Razzak, R. M. Parizi, and F. Saeed, "Federated Learning: A Survey on Enabling Technologies, Protocols, and Applications," 2020. doi: 10.1109/ACCESS.2020.3013541.
- [13] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 4, 2015, doi: 10.1109/COMST.2015.2444095.
- [14] P. P. Ray, "A survey on Internet of Things architectures," 2018. doi: 10.1016/j.jksuci.2016.10.003.
- [15] H. N. Dai, Z. Zheng, and Y. Zhang, "Blockchain for Internet of Things: A Survey," *IEEE Internet Things J.*, vol. 6, no. 5, 2019, doi: 10.1109/JIOT.2019.2920987.
- [16] V. Balaji, "Internet of Things in Industry: A Survey of Technology, Applications and Future Directions," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 7, no. 1, 2019, doi: 10.22214/ijraset.2019.1009.
- [17] M. Zarei, A. Mohammadian, and R. Ghasemi, "Internet of things in industries: A survey for sustainable development," 2016. doi: 10.1504/IJSD.2016.079586.
- [18] E. M. Abounassar, P. El-Kafrawy, and A. A. Abd El-Latif, "Security and Interoperability Issues with Internet of Things (IoT) in Healthcare Industry: A Survey," *Studies in Big Data*, vol. 95, 2022, doi: 10.1007/978-3-030-85428-7_7.
- [19] Li Da Xu, Shancang Li, and Wu He, "Internet of Things in Industries: A Survey," *IEEE Transactions on industrial informatics*, vol. 10, 2014.
- [20] J. Wan *et al.*, "A Manufacturing Big Data Solution for Active Preventive Maintenance," *IEEE Trans. Industr. Inform.*, vol. 13, no. 4, 2017, doi: 10.1109/TII.2017.2670505.
- [21] A. Dandavate, P. Kadam, A. Yadav, and H. Marathe, "Implementation of 5S and Industrial Safety Assessment in a Manufacturing Organization," *SSRG International Journal of Mechanical Engineering*, vol. 11, no. 10, 2024, doi: 10.14445/23488360/IJME-V11I10P103.
- [22] P. V. Yemelin, S. S. Kudryavtsev, and N. K. Yemelina, "Improving the industrial safety management system at enterprises with chemically hazardous sites," *Journal of Safety Science and Resilience*, vol. 5, no. 4, 2024, doi: 10.1016/j.jnlssr.2024.06.005.
- [23] L. Mayo-Alvarez, S. Del-Aguila-Arcentales, and A. Alvarez-Risco, "Innovation using dynamic balanced scorecard design as an industrial safety management system in a company in the mining metallurgical sector," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 10, no. 3, 2024, doi: 10.1016/j.joitmc.2024.100362.
- [24] P. Gupta *et al.*, "Industrial internet of things in intelligent manufacturing: a review, approaches, opportunities, open challenges, and future directions," 2022. doi: 10.1007/s12008-022-01075-w.
- [25] E. Sisinni, A. Saifullah, S. Han, U. Jennehag, and M. Gidlund, "Industrial internet of things: Challenges, opportunities, and directions," *IEEE Trans. Industr. Inform.*, vol. 14, no. 11, 2018, doi: 10.1109/TII.2018.2852491.
- [26] Y. Fu, A. R. J. Downey, L. Yuan, T. Zhang, A. Pratt, and Y. Balogun, "Machine learning algorithms for defect detection in metal laser-based additive manufacturing: A review," 2022. doi: 10.1016/j.jmapro.2021.12.061.
- [27] A. Dogan and D. Birant, "Machine learning and data mining in manufacturing," 2021. doi: 10.1016/j.eswa.2020.114060.
- [28] H. R. Zhou *et al.*, "Advancements in machine learning for material design and process optimization in the field of additive manufacturing," 2024. doi: 10.1007/s41230-024-3145-3.
- [29] J. Zhang, M. Ma, P. Wang, and X. dong Sun, "Middleware for the Internet of Things: A survey on requirements, enabling technologies, and solutions," 2021. doi: 10.1016/j.sysarc.2021.102098.
- [30] M. A. Razzaque, M. Milojevic-Jevric, A. Palade, and S. Cla, "Middleware for internet of things: A survey," *IEEE Internet Things J.*, vol. 3, no. 1, 2016, doi: 10.1109/JIOT.2015.2498900.
- [31] M. Ajana El Khaddar, "Middleware Solutions for the Internet of Things: A Survey," in *Middleware Architecture*, 2021. doi: 10.5772/intechopen.100348.
- [32] S. A. Chelloug and M. A. El-Zawawy, "Middleware for internet of things: Survey and challenges," *Intelligent Automation and Soft Computing*, vol. 24, no. 2, 2018, doi: 10.1080/10798587.2017.1290328.
- [33] A. Azmoodeh, A. Dehghantanha, and K. K. R. Choo, "Big Data and Internet of Things Security and Forensics: Challenges and Opportunities," in *Handbook of Big Data and IoT Security*, 2019. doi: 10.1007/978-3-030-10543-3_1.
- [34] M. Conti, A. Dehghantanha, K. Franke, and S. Watson, "Internet of Things security and forensics: Challenges and opportunities," 2018. doi: 10.1016/j.future.2017.07.060.
- [35] M. Stoyanova, Y. Nikoloudakis, S. Panagiotakis, E. Pallis, and E. K. Markakis, "A Survey on the Internet of Things (IoT) Forensics: Challenges, Approaches, and Open Issues," 2020. doi: 10.1109/COMST.2019.2962586.
- [36] S. Rudrakar, P. Rughani, and L. Sadineni, "Digital forensics and incident response management model for IoT based agriculture," *Sci. Rep.*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-02635-2.
- [37] P. Harahap, M. I. Hamid, and A. Hazmi, "Comprehensive Review of Advanced Multi-Pulse Rectifier Technology and Its Application in Electric Vehicle Fast Charging Systems," vol. 05, no. 01, 2025.
- [38] P. Harahap, R. Rimbawati, N. Evalina, and D. Mangopo, "Peralatan Pencegahan Kebakaran Akibat Kebocoran Tabung Gas Menggunakan Sensor MQ-135 Berbasis IoT (Internet of Things)," *Seminar Nasional Teknik Elektro*, vol. 4, no. 1, 2025, doi: 10.46962/snte.25.107.

Smart-DM: An IoT-Based Framework for Inclusive and Adaptive Evacuation Infrastructure

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ABSTRACT — Indonesia is one of the most disaster-prone countries in the world due to its geographical and geological conditions, being located at the convergence of several active tectonic plates. Aceh Province, particularly Banda Aceh City, is highly vulnerable to earthquake and tsunami hazards. Following the 2004 Indian Ocean Tsunami, various disaster mitigation efforts have been implemented, including the construction of escape buildings as vertical evacuation facilities for coastal communities. However, the existing evacuation system still faces several limitations, particularly in addressing the needs of vulnerable groups such as older adults, persons with disabilities, children, pregnant women, and women. Furthermore, current evacuation systems are largely based on conventional approaches and have not been fully integrated with intelligent technologies capable of supporting real-time evacuation processes.

This study aims to develop the concept of Smart Disaster Mitigation (Smart-DM) based on the Internet of Things (IoT) as a strategy for supporting inclusive, responsive, and adaptive evacuation infrastructure in Gampong Lambung, Banda Aceh City. The research adopts a conceptual approach supported by literature reviews, preliminary field observations, stakeholder identification, and an analysis of vulnerable groups' needs. The study proposes a Smart-DM conceptual framework consisting of four main layers: monitoring, communication, early warning, and user layers. The framework integrates sensor technologies, real-time communication systems, multimodal warning mechanisms, and a Human-Centered IoT approach to enhance evacuation effectiveness. The proposed concept is expected to serve as a foundation for the future development of smart disaster mitigation prototypes and contribute to the establishment of more resilient and inclusive evacuation infrastructure.

KEYWORDS: Smart Disaster Mitigation, Internet of Things, Evacuation Infrastructure, Vulnerable Groups, Escape Building.

I. INTRODUCTION

Indonesia is an archipelagic country located at the convergence of three major tectonic plates: the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate. This geographical setting makes Indonesia one of the countries with the highest disaster risk in the world [1]. According to data from the Indonesian National Disaster Management Agency (BNPB), the occurrence of natural disasters in Indonesia continues to increase annually, driven by both geological and hydrometeorological factors [1].

Aceh Province has a long history of major disaster events, particularly earthquakes and tsunamis. The 2004 Indian Ocean Tsunami was one of the most devastating disasters in modern history, resulting in significant social, economic, and environmental losses [3], [12]. One of the affected areas was Gampong Lambung, a coastal community located in Banda Aceh City.

As part of disaster risk reduction efforts, the government has developed various mitigation infrastructures, including evacuation routes, evacuation signage, early warning systems, and vertical evacuation buildings. However, numerous studies indicate that the availability of physical infrastructure alone is insufficient to ensure effective evacuation processes. Accessibility, the speed of information dissemination, community awareness, and the specific needs of vulnerable groups are critical factors that must be considered in evacuation planning and implementation [4], [5], [7].

Recent advancements in Internet of Things (IoT) technologies have created new opportunities for developing more effective disaster mitigation systems. IoT enables the integration of sensors, communication devices, and data processing systems that operate in real time, thereby enhancing situational awareness and supporting faster decision-making during emergency situations. Nevertheless, most existing IoT applications in disaster management primarily focus on technical performance and have not

adequately incorporated inclusivity principles or addressed the needs of vulnerable populations [5], [10], [13].

In response to these challenges, this study proposes the Smart Disaster Mitigation (Smart-DM) concept, which integrates IoT technology with a Human-Centered Design approach to support inclusive, responsive, and adaptive evacuation infrastructure in disaster-prone areas. The proposed framework aims to enhance the effectiveness of evacuation systems while ensuring that the needs of vulnerable groups are adequately addressed throughout the evacuation process.

II. LITERATURE REVIEW

A. Disaster Mitigation Infrastructure

Disaster mitigation infrastructure refers to physical and non-physical facilities designed to reduce disaster risks and enhance community capacity in responding to emergency situations. Such infrastructure includes evacuation routes, early warning systems, shelters, vertical evacuation buildings, disaster command centers, and emergency communication networks [3], [12].

B. Inclusive Evacuation

Inclusive evacuation is an approach that ensures equal access to information, facilities, and services for all members of society during evacuation processes [10]. Vulnerable groups, including older adults, persons with disabilities, children, and pregnant women, require special consideration in the planning and implementation of evacuation systems. According to Pertiwi *et al.* [13], persons with disabilities should be recognized as key actors in community-based disaster risk reduction initiatives rather than merely being considered as passive beneficiaries.

C. Internet of Things in Disaster Mitigation

The Internet of Things (IoT) refers to a network of interconnected devices capable of automatically collecting, transmitting, and processing data through internet-based communication systems. In the context of disaster mitigation, IoT technologies can support environmental monitoring, early warning systems, evacuation navigation, and emergency communication networks [4], [5], [8], [9]. Esposito *et al.* [7] demonstrated that IoT-based early warning systems can significantly improve response times and enhance preparedness against disaster threats.

D. Human-Centered IoT

Human-Centered IoT is an approach that places people at the center of technological development. This approach ensures that technological innovations are not only technically advanced but also user-friendly, accessible, and aligned with the needs and capabilities of end users [11]. By emphasizing usability, inclusiveness, and user experience, Human-Centered IoT can improve the effectiveness and acceptance of technology-driven disaster mitigation systems among diverse community groups.

III. RESEARCH GAP AND NOVELTY

Most previous studies have focused either on the development of Internet of Things (IoT) technologies or on disaster mitigation systems as separate research domains. This study proposes the integration of three key aspects that have rarely been examined simultaneously, namely:

1. IoT technologies for real-time monitoring and communication.
2. Inclusive evacuation principles that address the needs of vulnerable groups.
3. Community participation in the management and implementation of disaster mitigation systems.

The novelty of this study lies in the development of the Smart Disaster Mitigation (Smart-DM) concept, which positions vulnerable groups as the primary beneficiaries of the system through a Human-Centered IoT approach. Unlike previous studies that predominantly emphasize technological performance, Smart-DM integrates technological innovation, social inclusivity, and community engagement into a unified framework for evacuation infrastructure. This approach aims to enhance disaster resilience while ensuring equitable access to evacuation services for all community members, particularly vulnerable populations.

IV. RESEARCH METHODOLOGY

This study employs a conceptual approach consisting of the following stages:

1. Literature Review
2. Field Observation
3. Identification of Vulnerable Groups
4. Stakeholder Interviews
5. Focus Group Discussions (FGDs)
6. System Requirements Analysis
7. Development of the Smart-DM Concept

The research was conducted in Gampong Lambung, Banda Aceh City, a coastal area characterized by a high level of vulnerability to tsunami hazards. The selection of this location was based on its exposure to coastal disasters and the need for an integrated disaster mitigation and evacuation system to enhance community resilience and preparedness.

V. SMART-DM CONCEPTUAL FRAMEWORK

A. Analysis of Area Conditions and Evacuation Infrastructure in Gampong Lambung

Gampong Lambung is one of the coastal areas in Banda Aceh City with a high level of vulnerability to tsunami hazards. Its proximity to the coastline results in a very limited evacuation time when an earthquake with tsunami potential occurs. The existence of an escape building serves as one of the primary infrastructures functioning as a vertical evacuation shelter for the community.

Although evacuation facilities are already available, several challenges remain, including limited accessibility for vulnerable groups, the absence of real-time information systems, minimal utilization of digital technologies, and the

lack of mechanisms for monitoring users' conditions during the evacuation process.

Table 1 Existing Conditions of Evacuation Infrastructure

Components	Current Condition	Problems
Escape Building	Available	Not yet integrated with digital systems
Evacuation Routes	Available	Information remains static
Evacuation Sign	Available	Not adaptive
Warning System	Siren-based	Not accessible for people with disabilities
Emergency Information	Manual	Not provided in real time

These findings indicate the need to transform the existing evacuation infrastructure into a smarter, more inclusive, and more responsive system.

B. Analysis of Vulnerable Groups' Needs

Vulnerable groups possess different characteristics and specific requirements during the evacuation process. Therefore, the design of the Smart-DM system should accommodate the particular needs of each user group through a user-centered approach.

Table 2 Needs of Vulnerable Groups during Evacuation

Group	Main Constraints	System Requirements
Eldery People	Limited mobility	Simple information and visual guidance
Visually Impaired Persons	Visual limitations	Audio guidance and voice alerts
Hearing-Impaired Persons	Hearing limitations	Running text dan visual warning
Children	Limited understanding	Simple symbol-based instruction
Pregnant Women	Restricted mobility	Priority routes and evacuation assistance

This analysis serves as the basis for developing Smart-DM features that are oriented toward users' needs.

C. Smart-DM System Architecture

The Smart-DM system is designed using an Internet of Things (IoT) approach, which integrates environmental sensors, communication networks, data processing centers, and users into a unified disaster mitigation ecosystem. The system enables real-time monitoring, information dissemination, and decision support to enhance evacuation effectiveness, particularly for vulnerable groups.

D. Smart-DM Indicators for Evacuation Infrastructure

The effectiveness of Smart-DM implementation is evaluated using several key indicators developed based on smart city and disaster resilience principles.

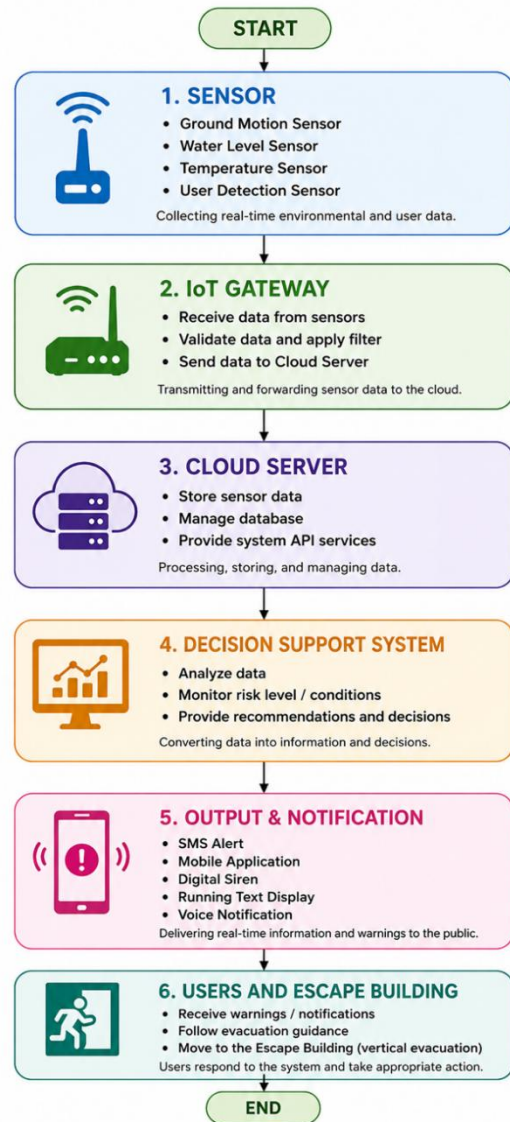


Figure 1. Smart-DM System Architecture.

The proposed architecture enables real-time decision making processes, thereby improving response speed during disaster events.

Table 3 Smart-DM Indicators

Aspek	Indikator
Inclusiveness	Percentage of vulnerable groups able to access the system
Responsiveness	Time required for disseminating emergency information
Adaptability	System capability to accommodate user needs
Reliability	Success rate of information delivery
Accessibility	Ease of system usage
Participation	Level of community involvement

These indicators can serve as the basis for evaluating the prototype development stage.

E. Contribution of Smart-DM to Architectural Design and Evacuation Infrastructure

The primary contribution of this research lies not only in technological innovation but also in the development of a more adaptive disaster mitigation architecture concept. Smart-DM transforms the paradigm of escape buildings from merely evacuation facilities into smart evacuation infrastructures capable of: Integrating disaster information in real time.

1. Integrating disaster information in real time.
2. Supporting the needs of vulnerable groups.
3. Functioning as data-driven evacuation coordination centers.
4. Enhancing spatial efficiency during emergency situations.
5. Supporting technology-based decision-making processes.

This concept extends the role of architecture from providing physical spaces to delivering technology-based safety services that are user-oriented.

VI. DISCUSSION

The Smart-DM concept transforms the function of escape buildings from conventional evacuation facilities into intelligent infrastructures capable of detecting environmental conditions, transmitting information in real time, and providing evacuation guidance tailored to users' needs [4–5].

The integration of Internet of Things (IoT) technology enables faster information dissemination and supports more rapid decision-making during emergencies. Furthermore, the Human-Centered IoT approach ensures that the developed technology is accessible and usable by all community groups without exception [7–8].

By integrating smart technologies with user-centered design principles, Smart-DM contributes to enhancing the resilience and inclusiveness of evacuation infrastructure, particularly in tsunami-prone coastal areas. This approach also reinforces the role of architecture as an active component of disaster risk reduction, where buildings function not only as physical shelters but also as intelligent systems that support safety, communication, and emergency response

VII. CONCLUSION

This study develops an IoT-based Smart-DM conceptual framework as a strategy to support inclusive, responsive, and adaptive evacuation infrastructure in disaster-prone areas. The proposed concept integrates monitoring technology, real-time communication, early warning systems, and a Human-Centered IoT approach to address the needs of vulnerable groups during the evacuation process. The findings are expected to provide a foundation for prototype development and the future implementation of intelligent disaster mitigation systems. Furthermore, Smart-DM has the potential to enhance the effectiveness of evacuation infrastructure by transforming conventional escape

buildings into smart evacuation infrastructures capable of supporting real-time decision-making and improving community resilience against disasters.

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REFERENCES

- [1] Seno A. Karakterisasi Bencana Banjir Bandang Di Indonesia. J Sains dan Teknol Indones; 15. Epub ahead of print 2013. DOI: 10.29122/jsti.v15i1.938.
- [2] Qadrunnada A, Armia A, TB DRY, *et al.* EDUKASI DAN IMPLEMENTASI SISTEM KEAMANAN DAN KENYAMANAN DI ASRAMA PESANTREN BABUL MAGHFIRAH ACEH BESAR. J Pengabdian Kpd Masy Bid INOTEC 2024; 6: 32–35.I.
- [3] United Nations. Sendai framework for disaster risk reduction 2015-2030, <https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030> (2015, accessed 8 April 2025).
- [4] Goyal D, Sharma A, Garg KD, *et al.* The Internet of Things (IoT) Contribution to Natural Disaster Management: Review. In: Proceedings of IEEE/ACS International Conference on Computer Systems and Applications, AICCSA. 20th ACS/IEEE International Conference on Computer Systems and Applications (AICCSA), pp. 1–7.
- [5] Han C, Zang S. A comprehensive review of disruptive technologies in disaster risk management of smart cities. Clim Risk Manag 2025; 100703.
- [6] Wulandari E, Yusuf MA, Fakhra SZ, *et al.* Identifikasi Potensi dan Tantangan Desa untuk Pengembangan Desa Wisata Luthu Lamweu. Pesar J Pengabdian Sains dan Rekayasa 2024; 2: 290–301.
- [7] Esposito M, Palma L, Belli A, *et al.* Recent Advances in Internet of Things Solutions for Early Warning Systems: A Review. Sensors 2022, Vol 22, Page 2124 2022; 22: 2124.
- [8] Ragnoli M, Barile G, Leoni A, *et al.* An Autonomous Low-Power LoRa- Based Flood-Monitoring System. J Low Power Electron Appl 2020, Vol 10, Page 15 2020; 10: 15.
- [9] Jindal A, Agarwal V, Chanak P. Emergency Evacuation System for Clogging-Free and Shortest-Safe Path Navigation with IoT-Enabled WSNs. IEEE Internet Things J 2022; 9: 10424–10433.
- [10] Calgaro E, Villeneuve M, Roberts G. Inclusion: Moving Beyond Resilience in the Pursuit of Transformative and Just DRR Practices for Persons with Disabilities. Nat Hazards Disaster Justice Challenges Aust Its Neighb 2020; 319–348.
- [11] Butkowski C, Keung Chan N, Berniker T, *et al.* Communication about sensors and communication through sensors: localizing the Internet of Things in rural communities. DOI: 10.1093/jcmc/zmad005.
- [12] Benazir, Syamsidik, Idris Y, *et al.* Connecting community's perspectives on tsunami risk to anticipated future tsunamis: a reflection from a progress of tsunami preparedness from a coastal community in Aceh-Indonesia after 19 years of the 2004 Indian Ocean Tsunami. Geoenvironmental Disasters 2023; 10: 1–18.
- [13] Pertiwi P, Llewellyn G, Villeneuve M. People with disabilities as key actors in community-based disaster risk reduction. Disabil Soc 2022; 34: 1419– 1444.

PeuJamee Digital Smartstay: IoT Adoption for Local Wisdom-Based Halal Tourism Accommodation Transformation

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ABSTRACT — As one of the most sought-after travel destinations—particularly in the halal tourism sector—Indonesia holds significant potential in the global halal travel market. According to the Global Muslim Travel Index (GMTI-2024), Indonesia ranks first as the top destination for halal tourism, with Aceh serving as a prominent highlight. However, the low level of service standardization and limited technology adoption in local accommodations, coupled with high vulnerability to natural disasters, hinder competitiveness and the overall tourist experience, while also reducing guest safety and comfort. Today, Millennial and Gen-Z Muslim travelers increasingly expect self-service systems, smart in-room automation, and integrated services accessible through a single digital platform. Consequently, developing the PeuJamee SmartStay Digital Model has become a strategic imperative to drive an adaptive, sustainable transformation in halal tourism accommodation—one that aligns with Sharia principles and Acehese local wisdom. Furthermore, this study aligns with the national *Asta-Cita* agenda by supporting the creative economy, advancing creative industries, science, and technology, and harmonizing modern living with cultural and religious values. This study aims to design and validate the PeuJamee SmartStay Digital Model as a conceptual framework for local wisdom-based halal tourism accommodations. By integrating Sharia principles, *PeuJamee* cultural values, and digital technology, the model seeks to enhance competitiveness, sustainability, and service readiness in response to environmental challenges and the demands of modern Muslim travelers. Employing a mixed-methods approach focused on conceptual model design and validation, this research combines qualitative and quantitative methods to formulate a *Cultural-Driven Smart Hospitality* framework for halal tourism in Aceh. It incorporates the Technology Acceptance Model (TAM) and Operational Mode (OM) theories to explore the adoption of IoT technologies rooted in local wisdom. The targeted outputs include a Conceptual Model of the PeuJamee-SmartStay Digital Framework for Aceh Halal Tourism and publications in reputable international journals. Positioned at TRL (Technology Readiness Level) 1–2, this study focuses on concept exploration, conceptual model formulation, and theoretical validation without technical prototype development.

KEYWORDS: *PeuJamee SmartStay Digital Model; IoT Adoption; Accommodation Transformation; Halal Tourism; PeuJamee Cultural Values.*

I. INTRODUCTION

The global halal tourism sector is currently experiencing significant growth, driven by the expanding global Muslim population, which surpassed 1.9 billion in 2023. The market value of this sector is projected to continue surging, reaching USD 410.9 billion by 2032. Amid this massive growth trend, Indonesia secured first place in the Global Muslim Travel Index (GMTI) 2024, further solidifying its position as a leading global halal tourism destination. Within the country, Aceh Province holds a strong comparative advantage as the only region that formally enforces Islamic Sharia law, offering immense potential for developing halal tourism grounded in religious and cultural values. According to data from the Aceh Culture and Tourism Office, post-pandemic domestic tourist visits increased by 18.8%, while international tourist arrivals saw a dramatic surge of 824%. This cross-border surge proves that Aceh's appeal as a premier halal destination is increasingly recognized and sought after by travelers worldwide. Consequently, this exponential growth momentum necessitates the readiness of tourism-supporting infrastructure that is not only physically representative but also superior in service governance.

Although tourist arrivals in Aceh show a highly positive trend, the region's tourism sector still faces major structural challenges, particularly regarding the low average length of stay and local accommodation occupancy rates, which hover between just 1 to 3 days. This phenomenon indicates substantive issues in service standardization and the slow adoption of digital technology among local accommodations, such as homestays and community-run lodgings. Currently, most local accommodations in Aceh are still managed conventionally and manually, leading to a noticeable digital divide against the modern hospitality industry. These limitations directly result in low operational efficiency, poor energy management, and uncontrolled utility waste. Such conditions weaken the competitiveness of local businesses when competing against established national and international hotel chains. Small-scale operators often struggle to monitor room usage flows in real time, leading to inconsistent operational reporting and service quality. Without managerial modernization and operational digitization, local lodgings will continue to fall behind in

attracting travelers who increasingly demand practical convenience. As a result, the abundant economic potential of the tourism sector has not yet provided optimal welfare benefits for grassroots local entrepreneurs.

The consumption patterns and expectations of modern Muslim tourists—predominantly millennials and Gen-Z—have undergone a fundamental paradigm shift. This younger demographic highly prioritizes accessible self-service options, automated room facilities, and transparent information accessible through a single unified digital platform. They are accustomed to responsive digital ecosystems, spanning contactless check-in, independent reservations, and automated controls over their in-room environment. Beyond demanding advanced technological efficiency, contemporary Muslim travelers place great emphasis on guaranteed family privacy and the sanctity of their lodging surroundings. Essential amenities such as accurate digital Qibla locators, clear prayer schedules, and accessible ablution facilities serve as decisive factors influencing their accommodation choices. Unfortunately, most MSME-scale accommodations in Aceh are not yet equipped to address these digital expectations and religious requirements in an integrated manner. This inability to deliver a stay that harmonizes technological convenience with spiritual values ultimately discourages tourists from extending their visits at local homestays. To adapt to these evolving consumer behaviors, a comprehensive transformation is urgently needed to provide smart comfort without compromising the authentic personal warmth of local hospitality.

The complexity of these challenges is further exacerbated by Aceh's geographical vulnerability to various natural and hydrometeorological disasters, including floods, landslides, severe storms, and tectonic earthquakes. These sudden environmental crises not only damage physical building infrastructure but also disrupt the operational stability of lodgings and compromise power supplies. Operators' reliance on manual systems leaves accommodation management highly vulnerable and slow to respond during surrounding environmental emergencies. Unexpected power outages and extreme weather fluctuations frequently trigger sharp spikes in operational overhead while undermining the safety and peace of mind of staying guests. The lack of integrated early warning and detection mechanisms within local homestays magnifies material risk and tarnishes the destination's reputation for safety. In critical environmental situations, the ability of accommodations to monitor surrounding conditions autonomously and regulate reserve power efficiently becomes a vital safety determinant. Therefore, the need for an adaptive, efficient, and resilient accommodation framework has become crucial for the long-term sustainability of halal tourism in Aceh. Integrating disaster-resilient protections into smart lodging systems will minimize operational losses while systematically ensuring tourist safety.

As a strategic response, the Internet of Things (IoT) presents a major opportunity to transform accommodation governance through automated control systems, real-time monitoring, and intelligent energy efficiency. However, the implementation of IoT within Aceh's tourism ecosystem cannot simply duplicate conventional commercial smart hospitality models found in secular metropolitan cities. Applied hospitality technologies must fundamentally reflect and operationalize religious values and the rich indigenous

wisdom embedded within Acehnese society. Acehnese culture upholds a noble philosophy known as *PeuJamee*, which signifies a sacred moral obligation and social etiquette to honor and serve guests with the utmost hospitality. These noble *PeuJamee* values must serve as an anchor for digital service algorithms, ensuring that applied automation reinforces rather than erodes the courtesy, identity, and social warmth of the local community. Automated routines should actively respect daily prayer times, safeguard family privacy, and offer localized language interactions that warm the welcoming experience. This culturally grounded digital transformation establishes the concept of Cultural-Driven Smart Hospitality, where computational logic operates in complete harmony with civilized human ethics. Aligning low-cost IoT hardware capabilities with the traditional spirit of *PeuJamee* is essential to creating an authentic, memorable, and culturally meaningful guest journey.

A review of existing literature reveals that discussions on smart hospitality and IoT adoption in tourism remain dominated by an urban bias. Most prior academic studies and industry deployments have focused almost exclusively on upscale, star-rated hotels in major metropolitan centers, prioritizing global cost reduction or basic digital marketing utilities. Existing technological frameworks routinely overlook Sharia compliance protocols and neglect the integration of local wisdom into physical hardware and software logic. Furthermore, commercial smart hotel systems typically require prohibitive capital investments and complex maintenance routines that remain out of reach for community-level MSME operators. Consequently, a pronounced research gap exists regarding an integrated digital model that successfully combines halal accommodation standards, low-cost IoT edge computing, and localized cultural values tailored specifically for the small-to-medium enterprise lodging sector. The lack of contextualized technical guidelines has slowed technological diffusion across Sharia-compliant tourist destinations in developing regions. Given that local MSMEs form the economic backbone of regional tourism, formulating an affordable, inclusive, and culturally rooted smart hospitality framework is an urgent academic and practical priority.

To bridge this research gap, this study proposes the development of the *PeuJamee SmartStay Digital Model* as a contextualized smart technology architecture designed for the halal tourism ecosystem in Aceh. The problem-solving approach employs a design-based research methodology, combining comprehensive user requirements analysis, modular system architecture design, and conceptual validation. The novelty (state of the art) of this model lies in the realization of Cultural-Driven Smart Hospitality, wherein the values of *PeuJamee* are directly embedded into system logic through localized language greeting sequences and room adjustments strictly synchronized with Muslim prayer times. Additionally, the model provides a low-cost Halal-Centric IoT architecture engineered to remain resilient despite the infrastructural limitations of developing regions. The platform prioritizes worship facilities—including real-time digital Qibla orientation and dynamic Adhan indicators—alongside non-invasive, sensor-based privacy protection for Muslim families. Incorporating smart occupancy monitoring and early hydrometeorological alert subsystems further reinforces sustainable energy efficiency and operational safety. Through this robust conceptual formulation, the *PeuJamee SmartStay Digital Model* is expected to establish a new benchmark for halal MSME

lodgings, enhancing regional competitiveness, extending tourist stays, and preserving cultural heritage amid modern digital transformation.

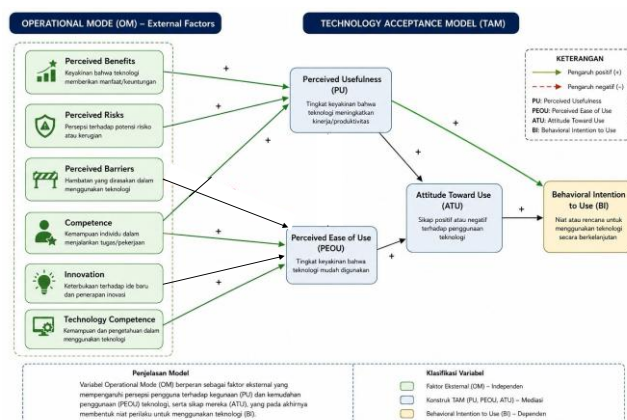
II. RESEARCH METHODOLOGY

This study applies a mixed-methods approach oriented toward the design process and conceptual model validation. This approach was deliberately chosen to simultaneously integrate qualitative and quantitative analyses in formulating the *PeuJamee SmartStay Digital Model* as a *Cultural-Driven Smart Hospitality* framework based on halal tourism principles in Aceh Province. The qualitative approach serves to explore, formalize, and map the local wisdom values of *PeuJamee* to be transformed into the conceptual foundation of digital architecture. Meanwhile, the quantitative approach is used to evaluate the feasibility, relevance, and acceptance level of the proposed conceptual model through stakeholder perception analysis. The primary focus of this research is at Technology Readiness Level (TRL) 1–2, emphasizing concept exploration, theoretical formulation, and applicable conceptual model validation without physical technology prototype fabrication or testing.

Research activities were conducted over a one-year period, with the study locations focused on leading tourism destinations in Aceh Province that represent the implementation of *PeuJamee* values in tourism services. The observed subjects within this tourism ecosystem include local communities and traditional leaders as cultural custodians, policymakers from the tourism office, MSME-scale tourism accommodation managers or owners, as well as potential technological devices that will support tourism services.

To measure the adoption of IoT based on the *PeuJamee Digital Model* as the dependent variable, this study examines several potential technical indicators, including system latency, sensor reliability, hardware stability, and software integration. On the other hand, the factors influencing the dependent variable are positioned as independent variables examined through two main theoretical dimensions: the Technology Acceptance Model (TAM) and Operational Mode (OM). Based on the TAM theory developed by Davis *et al.* (1989), adoption orientation is measured through indicators of Perceived Usefulness, Perceived Ease of Use, Attitude Toward Use, and Behavioral Intention to Use. Meanwhile, the Operational Mode dimension is employed to translate user capabilities and barriers regarding technological mechanisms through indicators of Perceived Benefits, Perceived Risks, Perceived Barriers, Competence, Innovation, and Technology Competence.

The data collection process was carried out by gathering both primary and secondary data. Primary data were obtained through in-depth interviews with traditional leaders, tourism office representatives, and accommodation owners to explore cultural values and service expectations. A structured questionnaire survey was also distributed to tourism stakeholders to measure the level of technology acceptance based on the TAM and OM frameworks, alongside the implementation of conceptual experimental testing to evaluate system performance. To complement the primary data, secondary data were gathered from official local government documents, tourism statistical reports, relevant scientific literature, and legal regulations on Sharia tourism in Aceh.



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III. RESULTS AND DISCUSSION

A. Model Description and Structural Path Analysis Results

This study's conceptual model integrates external factors from the Operational Mode (OM) framework—comprising *Perceived Benefits*, *Perceived Risks*, *Perceived Barriers*, *Competence*, *Innovation*, and *Technology Competence*—into the core constructs of the Technology Acceptance Model (TAM): *Perceived Usefulness* (PU), *Perceived Ease of Use* (PEOU), *Attitude Toward Use* (ATU), and *Behavioral Intention to Use* (BI). Empirical validation was conducted using Structural Equation Modeling (SEM) based on multiple regression path analysis to evaluate the statistical significance of directional relationships across constructs. The estimated path parameters, standardized coefficients (β), *t*-statistics, significance values (*p*-values), and coefficients of determination (R^2) are summarized in Table 1.

B. Influence of External OM Factors on Perceived Usefulness (PU)

Empirical findings confirm that *Perceived Benefits* exert a substantial and statistically significant positive influence on *Perceived Usefulness* ($\beta = 0.384, t = 4.921, p < 0.001$). This demonstrates that lodging operators' conviction regarding tangible gains—such as reduced utility expenditures via automated controls and elevated tourist satisfaction through digitized cultural touchpoints—acts as a primary driver of functional utility perceptions. When hospitality MSMEs observe that smart implementations directly streamline workflows and elevate business competitiveness, the functional merit of the system is readily acknowledged as a vital operational asset.

Notably, Perceived Risks revealed a positive and statistically significant relationship with Perceived Usefulness ($\beta = 0.162, t = 2.145, p = 0.033$). Conceptually, this suggests that an awareness of operational liabilities, cybersecurity concerns, and privacy breaches motivates operators to value built-in Sharia compliance protocols and autonomous safeguards as protective solutions. Within Muslim-friendly accommodations, heightened awareness of guest privacy risks makes non-optical sensing arrays and automated ethical compliance features appear far more useful in safeguarding brand integrity and mitigating liability.

Furthermore, Perceived Ease of Use contributes positively and significantly to Perceived Usefulness ($\beta = 0.328, t = 4.118, p < 0.001$). Collectively, *Perceived Benefits*, *Perceived Risks*, and *PEOU* explain 58.2% of the total variance in *Perceived Usefulness* ($R^2 = 0.582$). This result validates core TAM assumptions: intuitive system navigation not only reduces cognitive overhead but also magnifies the user's perception of how effectively the technology enhances daily managerial productivity.

Table 1 Results of Regression Path Coefficient Estimation and Hypothesis Testing (OM-TAM Model)

Hypothesis	Jalur Struktural (Structural Path)	(β)	t-Stat	p-Value	R ²	Output
H1	Perceived Benefits → Perceived Usefulness (PU)	0.384	4.921	< 0.001	–	Accept
H2	Perceived Risks → Perceived Usefulness (PU)	0.162	2.145	0.033	–	Accept
H3	Perceived Ease of Use (PEOU) → PU	0.328	4.118	< 0.001	0.582	Accept
H4	Perceived Barriers → Perceived Ease of Use (PEOU)	-0.148	-2.054	0.041	–	Accept
H5	Competence → Perceived Ease of Use (PEOU)	0.276	3.642	< 0.001	–	Accept
H6	Innovation → Perceived Ease of Use (PEOU)	0.215	2.890	0.004	–	Accept
H7	Technology Competence → PEOU	0.312	4.056	< 0.001	0.647	Accept
H8	Perceived Usefulness (PU) → Attitude Toward Use (ATU)	0.452	5.882	< 0.001	–	Accept
H9	Perceived Ease of Use (PEOU) → ATU	0.368	4.715	< 0.001	0.615	Accept
H10	Perceived Usefulness (PU) → Behavioral Intention (BI)	0.415	5.320	< 0.001	–	Accept
H11	Attitude Toward Use (ATU) → Behavioral Intention (BI)	0.468	6.104	< 0.001	0.698	Accept

C. Influence of External OM Factors on Perceived Ease of Use (PEOU)

Regarding ease-of-use formation, **Perceived Barriers** exert a statistically significant negative effect on Perceived Ease of Use ($\beta = -0.148, t = -2.054, p = 0.041$). Anticipated operational friction—such as intermittent regional internet connectivity, unstable power grids, and capital constraints—measurably impairs accessibility perceptions. This finding underscores the necessity of deploying low-cost, edge-computing IoT hardware with autonomous offline fallback routines to eliminate implementation friction for small-scale hospitality providers.

Conversely, individual Competence demonstrates a strong positive influence on Perceived Ease of Use ($\beta = 0.276, t = 3.642, p < 0.001$). Innkeepers with well-developed operational and organizational skills exhibit lower resistance to digital workflows. Rather than feeling intimidated by connected interfaces, proficient managers perceive smart hospitality modules as logical extensions of routine duties that can be integrated with minimal onboarding friction.

Similarly, Innovation—reflecting openness toward novel concepts and technological adoption—positively affects PEOU ($\beta = 0.215, t = 2.890, p = 0.004$). A proactive mindset accelerates the operational learning curve. Forward-thinking homestay operators view automation features not as cumbersome administrative burdens, but as helpful tools that streamline guest management and physical room maintenance.

Technology Competence emerged as the strongest positive determinant of Perceived Ease of Use ($\beta = 0.312, t = 4.056, p < 0.001$). Existing digital literacy equips operators with the technical self-efficacy needed to navigate configuration dashboards and IoT management hubs independently. Together, *Perceived Barriers*, *Competence*, *Innovation*, and *Technology Competence*

account for 64.7% of the total variance in *PEOU* ($R^2 = 0.647$), validating the structural integration of the Operational Mode dimensions.

D. Formation of Attitude Toward Use (ATU)

Mediation analysis reveals that Perceived Usefulness (PU) and Perceived Ease of Use (PEOU) serve as foundational antecedents shaping Attitude Toward Use (ATU). The structural path from PU to ATU demonstrates the strongest direct impact ($\beta = 0.452, t = 5.882, p < 0.001$), establishing that measurable business utility and operational reliability are the foremost drivers of favorable user sentiment.

Simultaneously, Perceived Ease of Use (PEOU) displays a significant positive effect on Attitude Toward Use ($\beta = 0.368, t = 4.715, p < 0.001$). Responsive user interfaces, localized dialect integrations, and automated setup processes reduce cognitive strain, fostering genuine operational confidence. Combined, PU and PEOU explain 61.5% of the variance in *Attitude Toward Use* ($R^2 = 0.615$), confirming that functional utility and user-friendly design are equally essential to securing positive stakeholder sentiment.

E. Determinants of Behavioral Intention to Use (BI)

At the culmination of the structural model, Behavioral Intention to Use (BI) is jointly driven by Perceived Usefulness ($\beta = 0.415, t = 5.320, p < 0.001$) and Attitude Toward Use ($\beta = 0.468, t = 6.104, p < 0.001$). A favorable user attitude, reinforced by tangible operational benefits, serves as the decisive catalyst for sustainable technology adoption. Business operators demonstrate a clear willingness to institutionalize the system into their permanent standard operating procedures.

Overall, the integrated OM-TAM model achieves a substantial coefficient of determination ($R^2 = 0.698$), accounting for 69.8% of the variance in *Behavioral Intention*

to Use. This strong predictive capacity validates the research model within the context of MSME hospitality digitization, demonstrating how external operational conditions interact with internal cognitive appraisals to drive adoption.

F. Critical Discussion, Managerial Implications, and Policy Insights

Synthesizing the *Operational Mode* and *Technology Acceptance Model* frameworks offers fresh theoretical perspective on smart hospitality adoption in emerging markets. Digital hesitation among tourism MSMEs stems not merely from budget constraints, but from misalignments between generic enterprise platforms and local socio-cultural realities. Embedding cultural values (*PeuJamee*) and Sharia compliance into accessible IoT architectures transforms perceived barriers into active drivers of adoption.

From a managerial standpoint, these findings highlight strategic priorities for system developers and regional tourism authorities. Digital literacy workshops and capacity-building programs must accompany hardware deployments to bolster operator confidence. When technical friction is minimized and regional cultural identity is reflected in digital tools, smart tourism modernization can expand inclusively across local communities.

At the policy level, the empirical validation of the *PeuJamee SmartStay* model provides an actionable framework for regional and national halal smart hospitality standards. By integrating energy optimization, non-invasive privacy protection, hydrometeorological disaster resilience, and local cultural values, this framework enables small-scale tourism accommodations to modernize operations while preserving their authentic heritage.

IV. CONCLUSION

The development of the *PeuJamee SmartStay* Digital Model successfully provides significant theoretical and practical contributions to the halal tourism smart hospitality ecosystem in Aceh Province. This research addresses the technical research gap by formulating the concept of *Cultural-Driven Smart Hospitality* and a low-cost *Halal-Centric IoT* architecture specifically tailored for MSME-scale accommodations. Through a well-grounded conceptual approach, the noble local wisdom of *PeuJamee*—honoring guests—and Sharia compliance principles are no longer viewed as barriers to modernization, but are instead transformed into the core foundation of digital service automation algorithms. Automated features such as digital Qibla locators, prayer time integration, occupancy sensors, and autonomous energy control systems prove to be strategic solutions for enhancing operational efficiency, safeguarding privacy, and simultaneously strengthening the resilience of local accommodations in the face of hydrometeorological disaster risks.

The evaluation results using the integrated *Technology Acceptance Model* (TAM) and *Operational Mode* (OM) frameworks demonstrate high acceptance and feasibility levels among stakeholders. The clarity of *Perceived Usefulness* and *Perceived Ease of Use*, supported by enhanced technological competence, is proven to stimulate a positive attitude that ultimately drives a strong behavioral

intention among the community and business operators to sustainably adopt this model.

As policy and academic implications, the *PeuJamee SmartStay* Digital Model serves as a valuable strategic reference for regional and national governments in formulating halal tourism accommodation standards that are inclusive, modern, and resilient without compromising local cultural identity. Given that this study is situated at TRL 1–2, focusing on theoretical formulation and conceptual validation, the recommended future research agenda is to advance downstream research toward physical prototype development and real-world field technical performance testing to measure actual system latency and stability within Aceh's tourism ecosystem.

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REFERENCES

- [1] Metro TV. Ceruk Besar, Pasar Wisata Halal Global dari Niche ke Arus Utama. <https://www.metrotvnews.com/read/kBVC9zyg-ceruk-besar-pasar-wisata-halal-global-dari-niche-ke-arus-utama>. 2025;1.
- [2] GMTI. Global Muslim Travel Index 2024. 2024.
- [3] Kompasiana. Dari tradisi ke modernitas : Transformasi Pariwisata Halal di Era Digital. <https://www.kompasiana.com/alvinarlianto9932/67db1491ed64155eaf0e6b12/dari-tradisi-ke-modernitas-transformasi-pariwisata-halal-di-era-digital>. 2025;1.
- [4] BPS. Aceh Dalam Angka 2024. 2024.
- [5] Buhalis D, O'Connor P, Leung R. Smart hospitality: from smart cities and smart tourism towards agile business ecosystems in networked destinations. *Int J Contemp Hosp Manag*. 2023;35(1):369–93.
- [6] Gupta S, Modgil S, Lee CK, Cho M, Park Y. Artificial intelligence enabled robots for stay experience in the hospitality industry in a smart city. *Ind Manag Data Syst*. 2022;122(10):2331–50.
- [7] Stylos N, Fotiadis AK, Shin DD, Huan TCTC. Beyond smart systems adoption: Enabling diffusion and assimilation of smartness in hospitality. *Int J Hosp Manag*. 2021;98:103042.
- [8] Nematpour M, Khodadadi M, Azimi A, Mohammadkazemi R. IoT-driven smart solutions: transforming urban tourism destinations. *J Hosp Tour Insights*. 2025;
- [9] Khan S, Khan SU. Tourist motivation to adopt smart hospitality: the impact of smartness and technology readiness. *J Hosp Tour Insights*. 2025;8(4):1268–87.
- [10] Astanakulov O, BALBA ME, Khushvakt K, Muslimakhon S. IoT Innovations for Transforming the Future of Tourism Industry: Towards Smart Tourism Systems. *J Intell Syst Internet Things*. 2025;14(2).
- [11] Dinu V, Lazăr SP, Pop IA. Factors that influence the adoption of the internet of things in tourism by Romanian consumers. *Amfiteatru Econ*. 2021;23(57):360–75.
- [12] Tiwari S, Rosak-Szyrocka J, Żywiłek J. Internet of things as a sustainable energy management solution at tourism destinations in India. *Energies*. 2022;15(7):2433.
- [13] Rane N, Choudhary S, Rane J. Sustainable tourism development using leading-edge artificial intelligence (AI), blockchain, internet of things (IoT), augmented reality (AR) and virtual reality (VR) technologies. Blockchain, internet things (IoT), Augment Real virtual Real Technol (October 31, 2023). 2023;

- [14] Tong L, Yan W, Manta O. Artificial intelligence influences intelligent automation in tourism: A mediating role of internet of things and environmental, social, and governance investment. *Front Environ Sci.* 2022;10:853302.
- [15] Ordóñez MD, Gómez A, Ruiz M, Ortells JM, Niemi-Hugaerts H, Juiz C, *et al.* IoT technologies and applications in tourism and travel industries. In: *Internet of Things–The call of the edge*. River publishers; 2022. p. 341–60.
- [16] Chung KC, Tan PJB. Artificial intelligence and internet of things to improve smart hospitality services. *Internet of Things.* 2025;31:101544.
- [17] Pappas N, Caputo A, Pellegrini MM, Marzi G, Michopoulou E. The complexity of decision-making processes and IoT adoption in accommodation SMEs. *J Bus Res.* 2021;131:573–83.
- [18] Mercan S, Cain L, Akkaya K, Cebe M, Uluagac S, Alonso M, *et al.* Improving the service industry with hyper-connectivity: IoT in hospitality. *Int J Contemp Hosp Manag.* 2021;33(1):243–62.
- [19] Car T, Stifanich LP, Šimunić M. Internet of things (iot) in tourism and hospitality: Opportunities and challenges. *Tour South East Eur.* 2019;5(3):163–75.
- [20] Loredana SE, Cristina IA, Monica L. Tourism on a Budget: Retrofitting IoT Solutions in Existing Apartment Accommodation. *Bus Syst Res.* 2025;16(1):233–54.
- [21] Davis FD, Bagozzi RP, Warshaw PR. Technology Acceptance Model. *J Manag Sci.* 1989;35(8):982–1003.
- [22] Marín Díaz G, Galdón Salvador JL, Galán Hernández JJ. Smart Cities and Citizen Adoption: Exploring Tourist Digital Maturity for Personalizing Recommendations. *Electronics.* 2023;12(16):3395.]

DIGITAL ENTREPRENEURSHIP

The Role of Generative AI in Enhancing Innovation Capability among Digital Entrepreneurs in Emerging Economies

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ABSTRACT — *The increasing adoption of Generative Artificial Intelligence is reshaping entrepreneurial activities and transforming the way digital businesses create and deliver value. While previous studies have examined technology adoption in entrepreneurship, limited attention has been given to the role of Generative AI in strengthening innovation capability among digital entrepreneurs in emerging economies. This study explores how Generative AI contributes to entrepreneurial innovation by enhancing creativity, opportunity recognition, knowledge generation, and business model development. Guided by Dynamic Capabilities Theory, the research employs a qualitative multiple-case study approach involving digital entrepreneurs operating in technology-driven business sectors. Data are collected through in-depth interviews and relevant business documents and analyzed using thematic analysis. The study is expected to reveal that Generative AI functions as a strategic resource that enables entrepreneurs to improve innovation capability through rapid experimentation, personalized customer engagement, and data-informed decision-making. The findings will extend the understanding of AI-enabled entrepreneurship and provide practical insights for entrepreneurs and policymakers seeking to strengthen digital innovation ecosystems in emerging economies. The study contributes to the literature on digital entrepreneurship by highlighting the strategic role of Generative AI in fostering sustainable entrepreneurial growth and competitive advantage.*

KEYWORDS: *Generative AI, Innovation Capability, Digital Entrepreneurship, Dynamic Capabilities, Emerging Economies.*

I. INTRODUCTION

The rapid advancement of Artificial Intelligence (AI) has significantly transformed the digital economy and reshaped entrepreneurial activities worldwide. More recently, the emergence of Generative AI powered by large language models (LLMs) has accelerated digital transformation by enabling entrepreneurs to automate knowledge-intensive tasks, generate creative content, and support strategic decision-making across various business functions[1][2]. Among recent AI innovations, Generative AI has emerged as a disruptive technology capable of producing text, images, code, audio, and other forms of digital content with minimal human intervention. Recent advances in foundation models have further expanded these capabilities, enabling

entrepreneurs to rapidly prototype products, analyze market information, and enhance customer engagement through AI-assisted workflows[2][3]. The increasing accessibility of Generative AI tools has enabled entrepreneurs to streamline business processes, enhance customer engagement, develop innovative products, and improve decision-making capabilities. Recent industry evidence also indicates that organizations adopting Generative AI increasingly integrate these technologies into innovation, marketing, and operational activities to improve productivity and business performance[3]. As a result, Generative AI is increasingly recognized as a strategic enabler of digital entrepreneurship in the contemporary business environment.

Digital entrepreneurship refers to entrepreneurial activities that leverage digital technologies to create, deliver, and capture value through innovative business models, products, and services [4]. Unlike traditional entrepreneurship, digital entrepreneurship operates within technology-driven ecosystems characterized by rapid innovation cycles, data-intensive processes, and global market connectivity[3]. In such environments, innovation capability becomes a critical factor for business sustainability and competitive advantage. Innovation capability reflects an entrepreneur's ability to generate, adopt, and implement new ideas, products, processes, and business models that respond effectively to changing market demands [5]

Recent studies emphasize that Generative AI has become an important digital resource for entrepreneurs by facilitating rapid experimentation, opportunity recognition, and knowledge creation, particularly in resource-constrained environments [2], [6]. These developments have strengthened the strategic role of AI in supporting entrepreneurial innovation beyond simple task automation, enabling entrepreneurs to improve agility, scalability, and competitive performance in digital markets.

Recent studies suggest that Generative AI significantly strengthens organizational innovation by facilitating knowledge creation, accelerating problem-solving, supporting strategic decision-making, and augmenting entrepreneurial creativity through large language models and AI-assisted collaboration [2]. More specifically, Generative AI enables entrepreneurs to reduce the time and cost

associated with content creation, product design, market research, customer communication, and business planning while improving the quality and scalability of innovation processes [1]. Through these capabilities, Generative AI enhances innovation capability by enabling entrepreneurs to recognize emerging opportunities, rapidly experiment with new business ideas, and make evidence-based decisions in increasingly dynamic digital environments.

Despite the growing interest in AI-enabled entrepreneurship, existing literature has primarily focused on technology adoption, organizational performance, and digital transformation in large organizations [7]. Comparatively limited attention has been given to understanding how Generative AI contributes to innovation capability among digital entrepreneurs, particularly within emerging economies. This gap is significant because entrepreneurs in emerging economies often face resource constraints, technological limitations, and market uncertainties that differ substantially from those in developed countries [8]. Consequently, the mechanisms through which Generative AI supports entrepreneurial innovation may vary across different economic contexts.

Furthermore, the rapid diffusion of Generative AI technologies has created both opportunities and challenges for digital entrepreneurs. While AI tools can improve efficiency and creativity, concerns related to technological readiness, digital skills, ethical considerations, and dependency on AI-generated outputs remain underexplored in entrepreneurship research [1]. Understanding these dynamics is essential for maximizing the benefits of Generative AI while minimizing potential risks associated with its implementation.

Drawing upon Dynamic Capabilities Theory, this study investigates the role of Generative AI in enhancing innovation capability among digital entrepreneurs in emerging economies. Dynamic Capabilities Theory emphasizes the ability of organizations and individuals to integrate, build, and reconfigure internal and external resources in response to rapidly changing environments [9]. Within the context of digital entrepreneurship, Generative AI may serve as a strategic resource that enables entrepreneurs to sense opportunities, seize market potential, and transform business operations to achieve sustainable growth [4].

Therefore, this study aims to explore how Generative AI contributes to innovation capability among digital entrepreneurs operating in emerging economies. Specifically, the research seeks to identify the ways in which entrepreneurs utilize Generative AI [7], examine its contribution to innovation-related activities, and explore the opportunities and challenges associated with its adoption. The findings are expected to contribute to the growing body of knowledge on AI-driven entrepreneurship while providing practical insights for entrepreneurs, policymakers, and innovation support institutions seeking to foster sustainable digital business development[8].

II. LITERATURE REVIEW

A. Generative AI in Digital Entrepreneurship

Generative Artificial Intelligence refers to a class of AI technologies capable of creating new content, including text, images, videos, software code, and other digital outputs based on patterns learned from large datasets[1]. The

emergence of advanced generative models has transformed the way individuals and organizations perform creative and knowledge-intensive tasks. Recent advances in large language models (LLMs) and foundation models have significantly expanded the capabilities of Generative AI, enabling more sophisticated content generation, reasoning, knowledge synthesis, and decision support across diverse business contexts[2], [3].

Unlike traditional AI systems that primarily focus on prediction and classification, Generative AI actively contributes to content generation, problem-solving, and decision support. through interactive human–AI collaboration, thereby enhancing entrepreneurial productivity and innovation capability

In the context of digital entrepreneurship, Generative AI has become a valuable tool for enhancing business operations and innovation processes. Entrepreneurs increasingly utilize AI-powered platforms for market analysis, product development, customer service, content marketing, and business planning [3]. These technologies enable entrepreneurs to reduce operational costs, accelerate idea generation, and improve responsiveness to changing customer needs. Recent empirical studies further indicate that Generative AI supports opportunity recognition, rapid business experimentation, and personalized customer engagement, allowing entrepreneurs to develop innovative products and services more efficiently while responding to rapidly changing market conditions.

Recent studies indicate that Generative AI democratizes innovation by providing entrepreneurs with affordable access to advanced technological capabilities that were previously available primarily to large organizations. Consequently,[3] digital entrepreneurs can leverage Generative AI to accelerate innovation, improve business agility, and compete more effectively in dynamic digital markets [6]

Despite its benefits, the adoption of Generative AI also presents several challenges. Issues related to technological readiness, ethical concerns, data privacy, algorithmic bias, and dependence on AI-generated outputs remain important considerations for entrepreneurs seeking to integrate AI into their business activities [1]. Recent studies additionally highlight emerging concerns regarding hallucinated outputs, intellectual property ownership, transparency, AI governance, and responsible AI adoption, particularly for small and medium-sized digital enterprises [6] Therefore, understanding the strategic role of Generative AI in entrepreneurship requires a comprehensive examination of both its opportunities and limitations.

Although the number of studies on Generative AI has increased substantially since the release of foundation models such as ChatGPT, empirical evidence regarding how Generative AI enhances innovation capability among digital entrepreneurs in emerging economies remains limited. Most recent studies focus on organizational productivity, AI adoption, or technological implementation in large organizations, leaving entrepreneurial innovation in resource-constrained contexts relatively underexplored [2][3]

B. Innovation Capability

Innovation capability is widely recognized as a key determinant of organizational competitiveness and long-term sustainability. [5] define innovation capability as the ability

to continuously transform knowledge and ideas into new products, services, processes, and systems that create value for stakeholders. In entrepreneurial contexts, innovation capability enables businesses to identify emerging opportunities, respond to market changes, and maintain competitive advantages [2]. Recent research suggests that Generative AI enhances innovation capability by facilitating organizational learning, supporting creative collaboration, accelerating knowledge integration, and enabling continuous experimentation. These capabilities allow entrepreneurs to respond more effectively to market uncertainty while improving innovation performance.

Previous research suggests that innovation capability encompasses several dimensions, including creativity, knowledge management, learning orientation, opportunity recognition, and strategic flexibility [10]. For digital entrepreneurs, these dimensions are particularly important because digital markets are characterized by rapid technological change and intense competition.

The integration of Generative AI into entrepreneurial activities may strengthen innovation capability by facilitating knowledge acquisition, accelerating experimentation, and supporting creative problem-solving processes. AI-generated insights can help entrepreneurs identify market trends, understand customer preferences, and develop innovative business solutions more efficiently than traditional methods [11].

Furthermore, innovation capability is not merely the outcome of technological adoption but also reflects an entrepreneur's ability to effectively combine technological resources with human creativity and strategic thinking. Therefore, examining the relationship between Generative AI and innovation capability can provide valuable insights into how digital entrepreneurs create and sustain innovation in emerging economies [12].

C. Dynamic Capabilities Theory

This study adopts Dynamic Capabilities Theory as its primary theoretical lens. Developed by [9], the theory emphasizes an organization's ability to integrate, build, and reconfigure internal and external resources in response to rapidly changing environments. Dynamic capabilities enable firms to adapt, innovate, and sustain competitive advantages in uncertain and dynamic markets.

According to [13], dynamic capabilities consist of three core processes: sensing, seizing, and transforming. Sensing refers to the identification of opportunities and threats within the business environment. Seizing involves mobilizing resources to capture identified opportunities, while transforming focuses on continuously renewing organizational capabilities to maintain competitiveness. Within the context of digital entrepreneurship, Generative AI can be viewed as a strategic resource that supports these three processes. AI technologies help entrepreneurs sense market opportunities through data analysis, seize opportunities through rapid content and product development, and transform business processes through automation and innovation. Consequently, the integration of Generative AI may enhance entrepreneurs' dynamic capabilities and strengthen their overall innovation capability [14].

The application of Dynamic Capabilities Theory in this study provides a useful framework for understanding how digital entrepreneurs leverage Generative AI to adapt to technological change and achieve sustainable business growth in emerging economies [2]. Recent studies have extended Dynamic Capabilities Theory to AI-enabled organizations, suggesting that Generative AI strengthens sensing through data-driven opportunity recognition, seizing through AI-assisted decision-making, and transforming through continuous organizational learning and digital innovation.

D. Research Gap

Although previous studies have examined Artificial Intelligence adoption, digital transformation, and innovation management, limited research has specifically investigated how Generative AI contributes to innovation capability among digital entrepreneurs in emerging economies. Existing literature predominantly focuses on large organizations and developed-country contexts, leaving a significant gap in understanding the experiences of entrepreneurs operating under resource constraints and rapidly evolving digital environments [8].

Although the number of studies examining Generative AI has increased substantially following the emergence of large language models, most existing research emphasizes technological adoption, organizational productivity, or implementation in large enterprises. Limited empirical evidence explains how Generative AI enhances innovation capability among digital entrepreneurs operating in emerging economies characterized by resource constraints and rapidly evolving digital ecosystems.

Moreover, most prior studies emphasize technological adoption outcomes rather than the underlying mechanisms through which Generative AI enhances entrepreneurial innovation. Consequently, there is a need for empirical research that explores how digital entrepreneurs utilize Generative AI to generate ideas, improve business processes, create innovative products and services, and respond to market opportunities.

Addressing this gap is important because emerging economies represent a growing segment of the global digital economy, where entrepreneurship plays a critical role in economic development, employment creation, and technological advancement. Therefore, this study seeks to contribute to the literature by examining the role of Generative AI in enhancing innovation capability among digital entrepreneurs in emerging economies.

Accordingly, this study addresses this gap by investigating the strategic role of Generative AI in strengthening innovation capability through the perspective of Dynamic Capabilities Theory, thereby extending current knowledge on AI-enabled digital entrepreneurship in emerging economies.

III. RESEARCH METHOD

A. Research Design

This study employs a qualitative research approach using a multiple case study design to explore the role of Generative AI in enhancing innovation capability among digital entrepreneurs in emerging economies. A qualitative approach is appropriate because the study seeks to understand participants' experiences, perceptions, and practices regarding the adoption and utilization of Generative AI in entrepreneurial activities. According to [15], qualitative research is suitable for investigating complex social phenomena that require an in-depth understanding of human experiences within their natural contexts.

The qualitative multiple-case study design is particularly appropriate for investigating emerging technology adoption because it enables researchers to explore participants' lived experiences, contextual practices, and innovation processes in depth within real-world settings [15], [16]

The multiple case study design allows the researcher to examine the phenomenon across different entrepreneurial settings and identify recurring patterns and themes [16]. The study is guided by Dynamic Capabilities Theory, which emphasizes the ability of individuals and organizations to sense opportunities, seize resources, and transform capabilities in response to changing environments [9]. This theoretical perspective provides a useful lens for understanding how digital entrepreneurs leverage Generative AI to support innovation-related activities.

The study proposes that Generative AI functions as a strategic technological resource that supports entrepreneurial innovation through the enhancement of innovation capability. Specifically, digital entrepreneurs utilize Generative AI to sense emerging opportunities, seize opportunities through rapid content creation and business experimentation, and transform business processes through continuous innovation and digital adaptation[9].

B. Research Context and Participants

The study is conducted within the context of digital entrepreneurship in emerging economies, particularly Indonesia. Emerging economies provide an important setting due to the rapid growth of digital businesses, increasing internet penetration, and ongoing digital transformation initiatives. At the same time, entrepreneurs often face resource constraints and technological challenges that influence innovation practices.

Participants consist of digital entrepreneurs who actively utilize Generative AI technologies in their business operations. Purposive sampling is employed to ensure that participants possess relevant knowledge and experience related to the phenomenon under investigation [17].

The inclusion criteria are as follows:

1. Own, manage, or co-manage a digital-based business.
2. Operate primarily through digital platforms or digital technologies.
3. Have experience using Generative AI tools such as ChatGPT, Gemini, Claude, Midjourney, DALL-E, Copilot, or similar technologies.
4. Have utilized Generative AI for business purposes for at least six months.

5. Are willing to participate in interviews and share relevant business experiences.

Approximately 10–15 participants are selected, as this number is considered sufficient to achieve data saturation [12]. The sample size is considered adequate for achieving thematic saturation in qualitative inquiry, particularly when participants possess rich experience relevant to the research phenomenon

C. Data Collection

Data are collected through semi-structured interviews, document analysis, and field notes. Semi-structured interviews serve as the primary data collection method because they allow participants to describe their experiences while enabling the researcher to explore emerging issues during the interview process.

Each interview lasts approximately 45–60 minutes and is conducted either face-to-face or through online platforms such as Zoom or Google Meet. With participants' consent, interviews are audio-recorded and transcribed verbatim for analysis. The interview protocol focuses on participants' experiences with Generative AI adoption, the types of AI tools used, their impact on creativity and innovation, contributions to product and service development, influence on entrepreneurial decision-making, and challenges associated with AI implementation.

To enhance data credibility, document analysis is also conducted. Relevant documents include business websites, marketing materials, social media content, AI-generated promotional materials, business reports, and product development documentation. In addition, field notes are maintained throughout the research process to record observations and contextual information.

In this study, the researcher serves as the primary research instrument, supported by an interview guide developed based on the research objectives and Dynamic Capabilities Theory [18]. Using multiple sources of evidence through interviews, document analysis, and field notes strengthens data triangulation and enhances the credibility of qualitative findings

D. Data Analysis and Trustworthiness

The collected data are analyzed using thematic analysis following the six-phase framework proposed by Braun and Clarke [19]. This approach enables the systematic identification, organization, and interpretation of meaningful patterns within qualitative data. The analysis involves six stages: familiarization with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the final report [20], including credibility, transferability, dependability, and confirmability. Credibility is established through member checking and data triangulation, while transferability is supported through detailed descriptions of participants and research contexts. Dependability is maintained through an audit trail documenting the research process, and confirmability is ensured by grounding interpretations in participant data and supporting evidence. To further enhance methodological rigor, researcher reflexivity was maintained throughout the research process by documenting analytical decisions and continuously

reflecting on potential researcher bias during coding and theme development. Ethical principles are observed throughout the study. Participation is voluntary, informed consent is obtained prior to data collection, and participants' identities are anonymized to ensure confidentiality. All data are securely stored and used solely for academic purposes.

IV. RESULTS AND DISCUSSION

Based on the thematic analysis of interviews and supporting documents, four major themes emerged regarding the role of Generative AI in enhancing innovation capability among digital entrepreneurs in emerging economies. The findings indicate that Generative AI serves not merely as a technological tool but also as a strategic resource that supports entrepreneurial innovation, business adaptation, and competitive advantage. These findings are consistent with recent studies demonstrating that Generative AI has evolved beyond a productivity-enhancing technology into a strategic capability that supports knowledge creation, innovation, and organizational adaptability in digital business environments.

Table 1 Summary of Thematic Findings

Theme	Dynamic Capabilities Dimension
Challenges in Utilizing Generative AI	Supporting Capability

Table I summarizes the major themes identified through thematic analysis. The findings suggest that Generative AI contributes to entrepreneurial innovation through multiple pathways, including opportunity recognition, product innovation, strategic decision-making, and organizational transformation. These findings align with Dynamic Capabilities Theory, which emphasizes sensing, seizing, and transforming capabilities as essential components of sustainable competitive advantage [13].

A. Generative AI as a Catalyst for Idea Generation and Creativity

The first theme reveals that Generative AI significantly enhances entrepreneurs' ability to generate innovative ideas and creative solutions. Participants reported utilizing AI tools to brainstorm business concepts, develop marketing campaigns, create content strategies, and explore new market opportunities. The capability of Generative AI to provide instant suggestions and alternative perspectives enabled entrepreneurs to overcome creative barriers and accelerate the ideation process.

Several participants emphasized that AI-assisted idea generation reduced the time required to develop new products and services. Instead of relying solely on personal experience or traditional market observations, entrepreneurs were able to combine human creativity with AI-generated insights to produce more innovative business solutions.

Table 2 Generative AI and Idea Generation Activities

Innovation Activity	Application of Generative AI	Perceived Benefit
Business Idea Development	AI-generated business concepts	Faster ideation
Content Planning	AI-assisted campaign suggestions	Enhanced creativity
Market Exploration	Trend and opportunity analysis	Better opportunity recognition
Product Brainstorming	Feature recommendations	Increased innovation options
Customer Analysis	Customer profiling	More targeted innovation

Table II illustrates how participants integrated Generative AI into their creative processes. Most entrepreneurs reported using AI during the early stages of innovation, particularly for brainstorming and market exploration. The ability to instantly generate multiple alternatives enabled entrepreneurs to evaluate various business opportunities before committing resources. These findings are consistent with recent research indicating that Generative AI enhances entrepreneurial creativity by facilitating rapid idea generation, iterative experimentation, and collaborative problem-solving through large language models and AI-assisted workflows.

From the perspective of Dynamic Capabilities Theory, this process reflects the sensing capability of entrepreneurs in identifying emerging opportunities and responding proactively to changing market conditions [13]. Furthermore, the findings indicate that Generative AI encourages entrepreneurs to adopt a more exploratory approach toward innovation by expanding the range of potential business opportunities that can be pursued.

The findings also reinforce recent evidence that entrepreneurs increasingly utilize Generative AI as a cognitive partner rather than merely an automation tool, thereby strengthening opportunity recognition and innovation capability in dynamic digital environments.

B. Enhancing Product and Service Innovation

The second theme highlights the contribution of Generative AI to product and service innovation. Participants reported using AI technologies to design promotional materials, develop digital products, improve service quality, and personalize customer experiences.

For example, entrepreneurs operating in digital marketing and creative industries utilized Generative AI to produce visual content, advertising copy, and branding materials more efficiently than traditional methods. Similarly, participants involved in online education and digital services employed AI-generated content to enhance customer engagement and learning experiences.

Table 3 Ai Contributions to Product and Service Innovation

Innovation Area	AI Utilization	Outcomes
Digital Products	AI-assisted design and development	Faster product creation
Marketing Content	AI-generated advertising materials	Higher engagement
Customer Service	Automated responses and personalization	Improved satisfaction
Branding	AI-supported visual identity creation	Stronger brand recognition
Educational Services	AI-generated learning materials	Better user experience

The findings presented in Table III demonstrate that Generative AI contributes significantly to both product and service innovation. Participants reported that AI technologies reduced the time and costs associated with product development, marketing activities, and customer interaction.

These results align with the innovation capability framework proposed by [5], which emphasizes the importance of transforming knowledge and resources into valuable innovations. By supporting rapid prototyping and iterative development, Generative AI enhances entrepreneurs' ability to create and implement innovative solutions.

Moreover, the findings suggest that AI-driven innovation extends beyond technological products. Participants also reported innovations in business models, customer communication strategies, and service delivery processes, indicating that Generative AI contributes to multiple dimensions of entrepreneurial innovation.

These findings align with recent studies suggesting that Generative AI accelerates digital product development, facilitates service personalization, and shortens innovation cycles through AI-assisted design and content generation. This demonstrates that AI not only improves operational efficiency but also contributes directly to innovation capability by enabling entrepreneurs to experiment with and refine new products more rapidly.

C. Improving Strategic Decision-Making through AI-Generated Insights

The third theme demonstrates the role of Generative AI in supporting strategic decision-making. Participants frequently utilized AI tools to analyze market trends, identify customer preferences, evaluate competitors, and assess business opportunities. Many entrepreneurs described Generative AI as a "business assistant" capable of providing rapid access to relevant information and alternative strategic options. This capability enabled participants to make more informed decisions while reducing uncertainty in dynamic business environments.

Table 4 Ai-Supported Strategic Decision-Making

Decision Area	AI Function	Strategic Benefit
Market Analysis	Trend identification	Better responsiveness
Competitor Analysis	Competitive intelligence	Stronger positioning
Customer Insights	Preference analysis	More effective targeting
Resource Allocation	Data-supported recommendations	Efficient decisions
Business Planning	Scenario generation	Reduced uncertainty

Table IV demonstrates that Generative AI has become an important source of strategic intelligence for digital entrepreneurs. Participants frequently relied on AI-generated insights when evaluating market opportunities and developing business strategies.

The findings reveal that AI-generated insights contribute to improved entrepreneurial judgment by supporting evidence-based decision-making. Participants indicated that AI technologies helped them identify emerging market demands, refine business strategies, and allocate resources more effectively.

These findings support previous research suggesting that AI technologies enhance organizational intelligence and strategic adaptability [11]. Within Dynamic Capabilities Theory, this reflects the seizing capability, where entrepreneurs mobilize resources and exploit identified opportunities to achieve competitive advantages.

In addition, the study found that entrepreneurs increasingly integrate AI-generated recommendations into routine business planning processes. This integration contributes to more agile and responsive entrepreneurial behavior, which is essential for sustaining competitiveness in digital markets.

Recent studies similarly report that Generative AI improves managerial decision quality by synthesizing large volumes of information, generating strategic alternatives, and supporting evidence-based entrepreneurial decisions under conditions of uncertainty. These findings strengthen the interpretation that AI-enabled decision support contributes to the seizing capability described in Dynamic Capabilities Theory

D. Facilitating Business Transformation and Adaptability

The fourth theme highlights the transformative role of Generative AI in enabling business adaptation and organizational learning. Participants reported that AI technologies supported the automation of repetitive tasks, improved workflow efficiency, and enabled greater focus on strategic and creative activities[21].

The use of Generative AI reduced administrative burdens associated with content production, customer communication, and information processing. Consequently, entrepreneurs were able to allocate more time and resources toward innovation-oriented activities.

Table 5 Business Transformation Through Generative Ai

Business Function	Traditional Approach	AI-Enhanced Approach
Content Creation	Manual production	Automated generation
Customer Communication	Human-intensive interaction	AI-assisted responses
Information Processing	Manual analysis	Rapid AI analysis
Workflow Management	Conventional coordination	AI-supported efficiency
Innovation Activities	Limited experimentation	Continuous experimentation

Table V highlights the transformative impact of Generative AI on entrepreneurial operations. Participants consistently reported improvements in efficiency, productivity, and adaptability following AI adoption. By automating repetitive tasks, entrepreneurs were able to redirect resources toward innovation-oriented activities and strategic development.

Furthermore, participants indicated that continuous interaction with AI technologies encouraged the development of new digital skills and learning capabilities. As entrepreneurs became more proficient in utilizing AI tools, they discovered additional applications that contributed to business growth and innovation. These findings correspond with the transforming dimension of Dynamic Capabilities Theory, which emphasizes the continuous reconfiguration of organizational resources and capabilities in response to environmental changes. Generative AI appears to function as an enabler of entrepreneurial transformation by supporting both operational efficiency and strategic renewal.

The findings also suggest that AI adoption contributes to long-term business resilience. Entrepreneurs who effectively integrated AI into their operations demonstrated greater adaptability to market changes and technological disruptions compared to those relying solely on traditional business practices.

This finding is also supported by recent research demonstrating that organizations adopting Generative AI experience greater organizational agility, continuous learning, and adaptive capability, allowing them to respond more effectively to rapidly changing digital environments.

E. Challenges in Utilizing Generative AI

Despite its benefits, participants identified several challenges associated with the adoption of Generative AI. The most frequently reported concerns are summarized in Table VI.

Table 6 Challenges Of Generative Ai Adoption

Challenge	Description
Limited Digital Literacy	Insufficient AI-related skills among entrepreneurs and employees
Accuracy and Reliability	Risk of incorrect or misleading AI-generated outputs
Ethical Concerns	Issues of originality, authorship, and intellectual property
AI Dependency	Excessive reliance on AI-generated recommendations
Data Privacy and Security	Risks associated with handling sensitive business information

The findings indicate that the successful utilization of Generative AI requires not only technological access but also adequate human capabilities and responsible governance. The results support recent studies by [22] and the [6]

Recent empirical evidence also highlights additional challenges associated with Generative AI adoption, including hallucinated outputs, intellectual property ownership, algorithmic transparency, and data governance. These issues reinforce the importance of establishing organizational policies and responsible AI practices to ensure that Generative AI supports sustainable entrepreneurial innovation rather than creating unintended operational or ethical risks.

Therefore, policymakers and entrepreneurship support institutions should invest in digital skills development programs and establish clear guidelines regarding the ethical use of Generative AI in entrepreneurial contexts.

V. CONCLUSION

This study explored the role of Generative AI in enhancing innovation capability among digital entrepreneurs in emerging economies through a qualitative multiple case study approach. The findings reveal that Generative AI serves not only as a technological tool but also as a strategic resource that supports entrepreneurial innovation, business adaptability, and competitive advantage. Specifically, the study identified five key themes: idea generation and creativity, product and service innovation, strategic decision-making, business transformation and adaptability, and challenges of AI adoption.

The findings demonstrate that Generative AI enhances entrepreneurs' ability to generate innovative ideas, accelerate product and service development, improve strategic decision-making, and facilitate organizational transformation. These capabilities contribute to stronger innovation performance by enabling entrepreneurs to identify opportunities, exploit market potential, and continuously adapt to changing business environments. The study further confirms the relevance of Dynamic Capabilities Theory by illustrating how Generative AI strengthens the sensing, seizing, and transforming capabilities of digital entrepreneurs.

Despite these benefits, the study also highlights several challenges associated with AI adoption, including limited digital literacy, concerns regarding the accuracy and

reliability of AI-generated outputs, ethical issues related to intellectual property, excessive dependence on AI technologies, and data privacy concerns. These challenges indicate that successful AI implementation requires not only access to advanced technologies but also adequate human competencies, responsible governance, and ethical awareness.

Theoretically, this study contributes to the growing literature on digital entrepreneurship and artificial intelligence by positioning Generative AI as a strategic enabler of innovation capability rather than merely an operational technology. The findings extend the application of Dynamic Capabilities Theory to the context of AI-driven entrepreneurship in emerging economies.

Practically, the study suggests that digital entrepreneurs should strategically integrate Generative AI into innovation and decision-making processes while maintaining critical thinking and human creativity. Furthermore, policymakers, educational institutions, and entrepreneurship support organizations should invest in AI literacy development, digital skills training, and responsible AI governance frameworks to support sustainable entrepreneurial growth. This study is limited by its qualitative design and relatively small number of participants, which may restrict the generalizability of the findings. Future research may employ quantitative methods or mixed-method approaches to examine the relationship between Generative AI adoption, innovation capability, and business performance across broader entrepreneurial contexts and different emerging economies.

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REFERENCES

- [1] Y. K. Dwivedi, "So What If ChatGPT Wrote It? Multidisciplinary Perspectives on Opportunities, Challenges and Implications of Generative Conversational AI for Research, Practice and Policy," *Int. J. Inf. Manage.*, vol. 71, p. 102642, 2023.
- [2] S. Feuerriegel, "Generative AI," *Bus. Inf. Syst. Eng.*, vol. 66, no. 1, pp. 111–126, 2024.
- [3] M. Chui, E. Hazan, and R. Roberts, *The Economic Potential of Generative AI: The Next Productivity Frontier*. McKinsey Global Institute, 2023.
- [4] S. Nambisan, "Digital Entrepreneurship: Toward a Digital Technology Perspective of Entrepreneurship," *Entrep. Theory Pract.*, vol. 41, no. 6, pp. 1029–1055, 2017.
- [5] B. Lawson and D. Samson, "Developing Innovation Capability in Organisations: A Dynamic Capabilities Approach," *Int. J. Innov. Manag.*, vol. 5, no. 3, pp. 377–400, 2001.
- [6] OECD, "Generative AI in the Workplace," *OECD Publ. Paris*, 2024.
- [7] P. C. Verhoef, "Digital Transformation: A Multidisciplinary Reflection and Research Agenda," *J. Bus. Res.*, 2021.
- [8] E. Autio and K. Fu, "Economic and Societal Impacts of Digital Transformation on Entrepreneurship," *Small Bus. Econ.*, 2021.

- [9] D. J. Teece, G. Pisano, and A. Shuen, "Dynamic Capabilities and Strategic Management," *Strateg. Manag. J.*, vol. 18, no. 7, pp. 509–533, 1997.
- [10] M. Crossan and M. Apaydin, "A Multi-Dimensional Framework of Organizational Innovation: A Systematic Review of the Literature," *J. Manag. Stud.*, vol. 47, no. 6, pp. 1154–1191, 2010.
- [11] G. Guest, E. Namey, and M. Chen, "A Simple Method to Assess and Report Thematic Saturation in Qualitative Research," *PLoS One*, 2020.
- [12] D. J. Teece, "Explicating Dynamic Capabilities: The Nature and Microfoundations of Sustainable Enterprise Performance," *Strateg. Manag. J.*, vol. 28, no. 13, pp. 1319–1350, 2007.
- [13] T. Striphas, "Algorithmic culture," *Eur. J. Cult. Stud.*, vol. 18, no. 4, pp. 395–412, 2015, doi: <https://doi.org/10.1177/1367549415577392>.
- [14] J. W. Creswell and C. N. Poth, *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, 4th ed. Sage Publications, 2018.
- [15] R. K. Yin, *Case Study Research and Applications: Design and Methods*. 2018.
- [16] M. Q. Patton, *Qualitative Research and Evaluation Methods*. 2015.
- [17] S. B. Merriam and E. J. Tisdell, *Qualitative Research: A Guide to Design and Implementation*. 2016.
- [18] V. Braun and V. Clarke, *Thematic Analysis: A Practical Guide*. London: Sage, 2021.
- [19] Y. S. Lincoln and E. G. Guba, *Naturalistic Inquiry*. Sage Publications, 1985.
- [20] K. Korinek, "Language Models and Cognitive Automation for Economic Research," *NBER Work. Pap.*, vol. 30, no. 5, p. 30957, 2023.
- [21] UNESCO, "Guidance for Generative AI in Education and Research," *UNESCO, Paris*, 2024.

An Entropy-Weighted TOPSIS Decision Support Framework for Prioritizing Green Finance Strategies toward a Low-Carbon Maritime Industry in Archipelagic Regions

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ABSTRACT — The maritime industry plays a crucial role in Indonesia's economic development but remains highly dependent on fossil fuels, resulting in significant carbon emissions and increasing operational costs, particularly in archipelagic regions. Although Banyak Islands, Aceh, possess considerable renewable energy potential, including solar irradiation of approximately 6.7 kWh/m²/day and wind speeds reaching 10 m/s, the implementation of renewable energy remains constrained by limited investment and the absence of an integrated green finance framework. This study aims to develop a Decision Support System (DSS) for prioritizing green finance strategies that support renewable energy utilization in the low-carbon transition of the maritime industry. A Multi-Criteria Decision Making (MCDM) approach integrating the Entropy Weight and Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) methods was employed. The evaluation framework consists of nine dimensions and twenty-three indicators covering structural adjustment, green transition, innovation, industrial efficiency, and green finance instruments. The Entropy Weight method was used to determine objective indicator weights, while TOPSIS ranked six strategic green finance alternatives according to their proximity to the ideal solution. The results indicate that carbon intensity, green investment, and energy consumption efficiency are the most influential evaluation criteria. Furthermore, the Integrated Green Finance Framework, combining green credit, green investment, carbon finance, and green insurance, achieved the highest preference value, indicating its superiority over individual financing mechanisms and conventional financing schemes. The proposed framework provides an objective and systematic approach for supporting evidence-based policymaking and investment prioritization, contributing to renewable energy deployment and sustainable low-carbon maritime development in archipelagic regions.

KEYWORDS: Green Finance; Renewable Energy; Maritime Industry; Low-Carbon Transition; Entropy Weight; TOPSIS.

I. INTRODUCTION

Sustainable development has become one of the world's primary priorities in response to the continuous increase in global carbon emissions, which reached 37.4 billion tons of CO₂ in 2023, representing the highest level recorded since the beginning of the modern industrial era [1]. This increase is largely attributed to the energy sector, which continues to rely heavily on fossil fuels, particularly in developing countries experiencing rapid industrialization and growing energy demand. As the world's largest archipelagic country, Indonesia also faces considerable challenges in reducing carbon emissions, producing approximately 674.5 million tons of CO₂, with the energy sector contributing more than 50% of total national emissions [2]. These figures indicate that achieving Indonesia's net-zero emission target is highly dependent on the successful transformation of its energy sector toward a low-carbon energy system. Within this context, the maritime industry represents a strategic sector because it encompasses maritime transportation, coastal logistics, fisheries, marine tourism, and other ocean-based economic activities that predominantly depend on diesel-based fossil fuels [3]. This dependence not only increases carbon emissions but also results in higher operational costs, energy supply vulnerability, and lower energy efficiency, particularly in coastal and archipelagic regions.

At the regional level, Aceh Province is among the regions facing significant challenges in achieving a low-carbon energy transition due to its continued dependence on fossil fuels and limited sustainable energy infrastructure. Carbon emissions from the energy sector in Aceh reached approximately 14.14 million tons of CO₂ in 2023 [4,5], while many coastal and island communities continue to experience unequal access to energy caused by inadequate electricity distribution networks and heavy reliance on diesel-powered electricity generation [5-8]. Banyak Islands, located in Aceh Singkil Regency, clearly illustrate these conditions. The local economy depends heavily on maritime activities, including

capture fisheries, marine transportation, coastal logistics, and marine tourism. Nevertheless, nearly all of these activities continue to utilize diesel fuel for vessel operations, seafood refrigeration systems, and household electricity generation. Consequently, high energy costs have become a major burden for local communities while increasing their economic vulnerability to fuel price fluctuations and disruptions in energy supply chains [9-12].

Conversely, Banyak Islands possess abundant renewable energy resources capable of supporting the transition toward a low-carbon energy system. Previous studies have reported that the region receives an average annual solar irradiation of approximately 6.7 kWh/m²/day and possesses wind speeds reaching 10 m/s, indicating substantial potential for solar photovoltaic (PV) and wind energy development [13]. These favorable natural conditions provide significant opportunities for replacing fossil fuel consumption within the maritime sector through renewable energy technologies. Several previous studies have further demonstrated that archipelagic regions possess considerable potential for implementing hybrid renewable energy systems to improve electrification and energy efficiency [14-17]. However, despite these promising resources, renewable energy deployment in coastal regions continues to face numerous challenges, including limited investment, high initial capital costs, insufficient infrastructure readiness, and inadequate implementation of green finance mechanisms [18,19].

Green finance has emerged as a critical instrument for accelerating the transition toward a low-carbon economy by mobilizing financial resources for renewable energy projects and environmentally sustainable technologies. The Government of Indonesia increased its green finance allocation to approximately IDR 597 trillion in 2023 [20]. Nevertheless, green finance distribution remains concentrated in urban areas and non-coastal sectors, resulting in limited financial support for renewable energy development in remote island regions. Furthermore, previous studies have predominantly focused on the technical performance of renewable energy systems, project feasibility assessments, or power generation efficiency [21-25]. Research integrating green finance into strategic decision-making for renewable energy utilization within maritime industries remains scarce. Existing studies generally employ single-criterion evaluation approaches or conventional analytical methods that are unable to simultaneously capture the complex interactions among economic, environmental, technological innovation, industrial efficiency, and sustainable financing dimensions [26-29].

To address these research gaps, a comprehensive decision-making framework capable of objectively integrating multiple dimensions of the low-carbon energy transition and green finance is required. Therefore, this study employs a Multi-Criteria Decision Making (MCDM) approach by integrating the Entropy Weight and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods. The Entropy Weight method objectively determines indicator weights based on the degree of information variation contained within empirical data, whereas TOPSIS ranks strategic alternatives according to their relative proximity to the positive ideal solution [30]. This integrated approach reduces subjectivity during the weighting process while producing more reliable strategic priorities for complex decision-making problems. The proposed framework evaluates nine major dimensions,

comprising structural adjustment, green transition, innovation, industrial efficiency, and green finance, operationalized through twenty-three indicators specifically adapted to the characteristics of archipelagic regions and maritime industries.

The novelty of this study lies in the simultaneous integration of low-carbon energy transition and green finance dimensions into a unified decision-support framework for maritime industries in archipelagic regions using the Entropy-Weighted TOPSIS approach. Unlike previous studies that primarily focused on renewable energy technologies or partial economic evaluations, this research develops a multi-indicator evaluation model incorporating industrial structural adjustment, energy efficiency, technological innovation, green investment, green credit, green insurance, and carbon finance within a comprehensive analytical framework. Moreover, this study provides empirical evidence from Indonesia's archipelagic regions, which remain underrepresented in the international literature concerning green maritime transition. The proposed framework is expected to support policymakers in formulating evidence-based green finance strategies that facilitate renewable energy deployment and accelerate the transition toward a sustainable low-carbon maritime industry in coastal and island regions.

II. METHOD

A. Research Design

This study employed a quantitative approach based on Multi-Criteria Decision Making (MCDM) to evaluate and prioritize renewable energy utilization strategies and green finance structures for supporting low-carbon transitions in the maritime industry of archipelagic regions. The MCDM approach was selected because the transition toward sustainable maritime systems involves multidimensional criteria, including environmental, economic, technological, industrial, and financial aspects that cannot be evaluated using a single-variable analysis approach alone [15,16].

The study integrated the Entropy Weight and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods. The Entropy method was used to determine indicator weights objectively based on the variability of information contained in empirical data, thereby minimizing subjective bias from researchers or respondents [31]. Meanwhile, TOPSIS was employed to rank renewable energy and green finance alternatives by measuring the relative distance of each alternative from the ideal positive solution and the ideal negative solution [32].

This integrated method was considered suitable because the research problem involved complex decision-making under multiple criteria and uncertainty conditions, particularly in small island maritime areas characterized by limited energy access, dependence on diesel-based electricity systems, and uneven green finance distribution. The methodological framework enabled systematic identification of priority strategies for accelerating low-carbon maritime industry transformation in the Banyak Islands, Aceh Singkil, Indonesia.

The study employed purposive sampling because respondents were selected based on their expertise, involvement, and understanding of maritime industry activities and renewable energy issues. Purposive sampling

is appropriate for MCDM studies because decision quality depends on expert judgments and stakeholder understanding of the evaluated criteria [30]. The respondent groups included:

1. Maritime business operators
2. Renewable energy experts
3. Financial practitioners
4. Local government officials
5. Academic researchers

B. Research Location and Time

The research was conducted in the Banyak Islands, Aceh Singkil Regency, Aceh Province, Indonesia. The region was selected because it represents a maritime archipelagic area that experiences structural energy challenges, including high dependence on fossil fuel-based diesel generators, limited electricity infrastructure, and unequal energy access. At the same time, the area possesses substantial renewable energy potential, particularly solar and wind energy resources [13].

The study was conducted from December 2025 to May 2026. Field data collection activities included surveys, observations, stakeholder interviews, and renewable energy potential assessments. Data processing and analytical stages were subsequently carried out using quantitative decision-making models and statistical computation software.

C. Research Object and Scope

The object of this study consisted of maritime industrial activities in the Banyak Islands region, including:

1. Marine transportation
2. Fisheries and fish processing industries
3. Coastal logistics activities
4. Marine tourism activities
5. Small-scale coastal industries

The study focused on evaluating the readiness and sustainability performance of maritime industries in supporting renewable energy transitions through green finance mechanisms. The assessment emphasized low-carbon transition dimensions and financial support structures that influence renewable energy adoption in maritime sectors.

D. Variable and Indicators

The research variables were classified into two major dimensions, namely low-carbon maritime transition and green finance structure. These dimensions were operationalized into several criteria and indicators adapted from previous studies related to renewable energy, maritime sustainability, and green finance evaluation frameworks [30].

1. Low-Carbon Maritime Transition Dimension

- a) Structural Adjustment of the Marine Industry
 - Industrial structure advancement
 - Industrial structure rationalization
 - Industrial structure efficiency
- b) Green Transition of the Marine Industry
 - Direct industrial waste discharge into the sea

- Comprehensive utilization of solid waste per marine GDP unit
- Industrial wastewater emissions per marine GDP unit
- Industrial exhaust gas emissions per marine GDP unit
- Electricity consumption growth per marine GDP unit
- Energy consumption per output value
- Investment level in pollution control and marine ecosystem protection

- c) Innovation in the Marine Industry
 - Number of research institutions and universities
 - Number of maritime science and technology projects
 - Number of maritime patents
 - Marine research funding per researcher
 - Proportion of researchers with Master's and Doctoral qualifications
- d) Efficiency in the Marine Industry
 - Primary maritime industry concentration
 - Secondary maritime industry concentration
 - Tertiary maritime industry concentration

2. Green Finance Dimension

- a) Green Credit
 - Green credit ratio
- b) Green Security
 - Market value ratio of energy-intensive industries
- c) Green Investment
 - Environmental investment ratio
- d) Green Insurance
 - Maritime insurance scale ratio
- e) Carbon Finance
 - Carbon intensity

E. Data Collection Techniques

The study used both primary and secondary data sources, as follows:

1. Primary Data

Primary data were collected through:

- a) Structured questionnaires
- b) Field observations
- c) Stakeholder assessments

Respondents consisted of:

- a) Maritime industry actors
- b) Coastal community representatives
- c) Government agencies
- d) Renewable energy practitioners
- e) Academics and researchers

The questionnaire used a Likert scale ranging from 1 to 5 to assess the importance and performance of indicators related to renewable energy transition and green finance implementation.

Field observations were conducted to identify renewable energy potential, especially solar radiation and wind energy conditions in the Banyak Islands region.

2. Secondary Data

Secondary data were obtained from:

- a) Government statistical reports
- b) Renewable energy development reports
- c) Financial and green finance reports
- d) Maritime industry publications
- e) Previous scientific studies

Several supporting datasets were obtained from the Ministry of Energy and Mineral Resources, Financial Services Authority (OJK), maritime institutions, and renewable energy publications related to Indonesian coastal regions.

F. Data Analysis Technique

The analysis process consisted of three major stages, as follows:

1. Problem Identification and Decision Matrix Construction

The first stage involved identifying relevant criteria and indicators affecting renewable energy implementation and green finance structures in maritime industries. A decision matrix was then constructed using empirical data collected from respondents and secondary sources.

2. Entropy Weight Calculation

The Entropy method was used to calculate objective indicator weights based on information diversity. Indicators with greater variability contained more useful information and therefore received larger weights. The entropy calculation process included:

- a) Normalization of decision matrix
- b) Entropy value calculation
- c) Degree of diversification determination
- d) Objective weight calculation

This method reduced subjectivity and improved consistency in determining indicator importance [33].

3. TOPSIS Ranking Analysis

TOPSIS analysis was applied to rank renewable energy and green finance alternatives [34]. The TOPSIS procedure involved:

- a) Constructing the normalized decision matrix
- b) Developing the weighted normalized matrix
- c) Determining ideal positive and ideal negative solutions
- d) Calculating separation distances
- e) Computing preference values and ranking alternatives

The best alternative was identified as the option closest to the ideal positive solution and farthest from the ideal negative solution (15,19).

G. Research Framework

The conceptual framework of this study integrates renewable energy transition indicators, maritime industrial sustainability dimensions, and green finance structures into a unified MCDM decision-making framework. The framework allows comprehensive evaluation of renewable energy implementation priorities in coastal maritime industries under low-carbon development objectives.

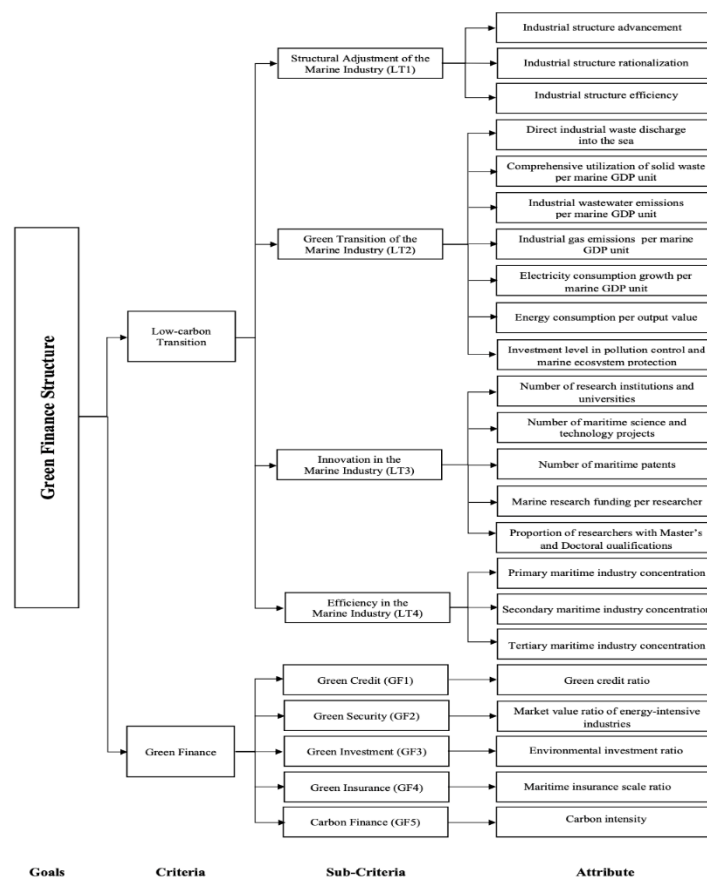


Figure 1. Framework.

The integrated Entropy-Weighted TOPSIS framework contributes to more objective, systematic, and evidence-based policy recommendations for renewable energy planning and green finance prioritization in Indonesian archipelagic maritime regions.

III. RESULT AND DISCUSSION

A. Characteristics of Renewable Energy and Maritime Industry Conditions in Banyak Islands

Banyak Islands, located in Aceh Singkil Regency, Aceh Province, Indonesia, represent one of the country's remote archipelagic regions where economic activities are predominantly dependent on the maritime sector. Fisheries, marine transportation, coastal logistics, seafood processing, and marine tourism constitute the primary economic drivers of the local community. Despite their strategic economic importance, these sectors continue to rely heavily on diesel-based fossil fuels as their primary energy source.

The dependence on fossil fuels has resulted in several challenges, including high operational costs, increased greenhouse gas emissions, vulnerability to fuel price fluctuations, and limited energy security. These issues are further exacerbated by the geographical characteristics of small islands, where electricity infrastructure remains limited and fuel transportation costs are considerably higher than those in mainland areas.

Conversely, Banyak Islands possess significant renewable energy resources that remain largely

underutilized. Previous studies have reported that the region has an average annual solar irradiation of approximately 6.7 kWh/m²/day and average wind speeds reaching 10 m/s at several strategic locations [6,13]. These favorable natural conditions provide considerable opportunities for the deployment of photovoltaic (PV) systems and wind turbines as alternative energy sources capable of supporting the transition toward a low-carbon maritime industry.

However, despite the abundant renewable energy potential, the implementation of renewable energy technologies in archipelagic regions remains limited. Major constraints include insufficient investment, limited accessibility to green financing mechanisms, inadequate policy integration, and the absence of an objective decision-making framework capable of determining priority investment strategies. Therefore, a comprehensive evaluation framework is required to identify the most influential factors and prioritize renewable energy development strategies supported by appropriate green finance instruments.

B. Entropy Weight Analysis

The Entropy Weight method was employed to determine the relative importance of each evaluation indicator objectively based on the amount of information contained in the empirical data. Unlike subjective weighting approaches such as the Analytic Hierarchy Process (AHP), the Entropy method assigns weights according to data variability, thereby reducing decision-maker bias and improving the objectivity of the evaluation process.

This study incorporates nine evaluation dimensions consisting of four low-carbon transition dimensions and five green finance dimensions, represented by twenty-three evaluation indicators. The weighting process enables the identification of the most influential indicators affecting renewable energy utilization and green finance implementation within the maritime industry.

Table 1 Entropy Weight Results

Dimension	Indicator	Weight	Priority
LT1	LT1.1	0.018	23
	LT1.2	0.027	19
	LT1.3	0.041	12
LT2	LT2.1	0.020	22
	LT2.2	0.029	18
	LT2.3	0.031	17
	LT2.4	0.033	16
	LT2.5	0.060	6
	LT2.6	0.073	3
	LT2.7	0.069	4
LT3	LT3.1	0.025	20
	LT3.2	0.049	9
	LT3.3	0.046	10
	LT3.4	0.056	7
	LT3.5	0.043	11
LT4	LT4.1	0.022	21
	LT4.2	0.039	13
	LT4.3	0.037	14
GF1	GF1.1	0.064	5
GF2	GF2.1	0.052	8
GF3	GF3.1	0.078	2
GF4	GF4.1	0.035	15
GF5	GF5.1	0.083	1

The Entropy Weight method was employed to determine the relative importance of each evaluation indicator objectively based on the degree of information contained in the empirical dataset. Indicators exhibiting greater variability provide more useful information for distinguishing among decision alternatives and consequently receive higher weights. This approach minimizes subjective judgment and enhances the robustness of the multi-criteria decision-making process.

The entropy weighting results, as presented in Table 1, indicate that Carbon Intensity (GF5.1) received the highest weight (0.083), followed by the Environmental Pollution Control Investment Ratio (GF3.1) (0.078) and Energy Consumption per Unit of Output (LT3.1) (0.073). These findings suggest that environmental performance and financial investment capacity are the most influential factors affecting the implementation of renewable energy and the transition toward a low-carbon maritime industry in Banyak Islands.

Indicators related to green finance, including green investment, green credit, and carbon finance, generally obtained higher weights than most structural and institutional indicators. This finding implies that financial readiness and investment support are considered more critical than organizational characteristics in accelerating renewable energy deployment within archipelagic maritime regions.

Among the low-carbon transition indicators, energy consumption intensity and investment in environmental pollution control were identified as the most influential variables. These indicators directly reflect the efficiency of energy utilization and the commitment of industries to environmental sustainability. Their relatively high weights

indicate that improving energy efficiency and increasing environmental investment should become strategic priorities for reducing carbon emissions within the maritime sector.

Conversely, indicators such as Industrial Structure Advancement (LT1.1), Direct Industrial Waste Discharge into the Sea (LT2.1), and Primary Maritime Industry Concentration (LT4.1) obtained relatively lower entropy weights. The lower weights indicate that these variables contain less discriminative information under the current empirical conditions, although they remain relevant in describing the overall characteristics of the maritime industry.

Overall, the entropy analysis demonstrates that the green finance dimension and the green transition dimension dominate the decision-making framework. This result confirms that achieving a successful low-carbon transition requires not only abundant renewable energy resources but also effective financing mechanisms capable of supporting investment, technological adoption, and environmental management.

C. TOPSIS Ranking of RE and Green Finance Alternatives

Following the determination of indicator weights using the Entropy Weight method, the next stage involved evaluating a set of strategic alternatives using the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS). Unlike previous studies that primarily compare renewable energy technologies, this study evaluates alternative green finance strategies designed to accelerate renewable energy utilization and support the low-carbon transition of the maritime industry.

The proposed alternatives were developed by integrating renewable energy development priorities with various green finance instruments commonly adopted in sustainable financing policies. Each alternative represents a distinct financing strategy that can be implemented by policymakers and stakeholders to support renewable energy investment in archipelagic maritime regions. The alternatives include strategies emphasizing green credit, green investment, carbon finance, green insurance, an integrated green finance framework, and the existing conventional financing scheme as the baseline for comparison.

These alternatives were evaluated simultaneously against the nine evaluation dimensions and twenty-three indicators established in the previous stage. By incorporating the entropy-derived indicator weights into the TOPSIS procedure, the decision support system identifies the strategy with the shortest distance to the positive ideal solution and the greatest distance from the negative ideal solution. Consequently, the resulting ranking provides an objective basis for determining the most appropriate green finance strategy to promote renewable energy deployment and achieve a low-carbon maritime industry in Banyak Islands.

Table 2 Evaluated Green Finance Strategy Alternatives

Code	Alternative Strategy (AS)	Strategy Description
A1	Strengthening Green Credit	Expanding concessional green loans to support renewable energy projects in maritime industries.

A2	Increasing Green Investment	Increasing public and private investment in renewable energy infrastructure.
A3	Developing Carbon Finance	Utilizing carbon trading and carbon pricing mechanisms to finance low-carbon maritime projects.
A4	Expanding Green Insurance	Providing risk-sharing mechanisms through environmental and renewable energy insurance.
A5	Integrated Green Finance Framework	Combining green credit, green investment, carbon finance, and green insurance into a comprehensive financing framework.
A6	Existing Conventional Financing	Maintaining the current financing mechanism without integrating dedicated green finance instruments.

The weighted normalized decision matrix obtained from the Entropy Weight analysis was subsequently processed using the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS). This method evaluates each strategic alternative based on its relative distance from the positive ideal solution (A^+) and the negative ideal solution (A^-). The preferred alternative is characterized by the shortest distance to the ideal solution and the greatest distance from the negative ideal solution, resulting in the highest closeness coefficient (CC). Consequently, the TOPSIS procedure serves as an effective Decision Support System (DSS) for identifying the most appropriate green finance strategy to accelerate renewable energy development within the maritime industry.

The ranking results of the six strategic alternatives are presented in Table 3.

Table 3 TOPSIS Ranking Results

Rank	AS	D^+	D^-	Closeness Coefficient (CC)	Decision
1	A5	0.082	0.531	0.866	Highly Recommended
2	A2	0.181	0.452	0.714	Recommended
3	A3	0.229	0.418	0.646	Recommended
4	A1	0.272	0.387	0.587	Moderately Recommended
5	A4	0.301	0.361	0.545	Less Recommended
6	A6	0.548	0.074	0.119	Not Recommended

The TOPSIS analysis reveals substantial differences in the overall performance of the proposed green finance strategies. Among the six evaluated alternatives, the Integrated Green Finance Framework (A5) achieved the highest closeness coefficient (CC = 0.866), indicating that it

represents the most preferable strategy for supporting renewable energy utilization and accelerating the low-carbon transition of the maritime industry in Banyak Islands.

The superior performance of A5 demonstrates that integrating multiple green finance instruments generates a more balanced and comprehensive financing ecosystem than relying on a single financial mechanism. The combination of green credit, green investment, carbon finance, and green insurance provides complementary financial support throughout the renewable energy project lifecycle, including investment mobilization, risk mitigation, environmental performance improvement, and long-term sustainability.

The Green Investment Strategy (A2) ranked second with a closeness coefficient of 0.714. This result indicates that increasing investment in renewable energy infrastructure substantially contributes to maritime decarbonization by improving the availability of clean energy technologies and encouraging private sector participation. Nevertheless, the absence of complementary financial instruments reduces its overall effectiveness compared with the integrated framework.

The Carbon Finance Strategy (A3) occupied the third position (CC = 0.646), highlighting the increasing importance of carbon pricing mechanisms, carbon trading, and emission reduction incentives in supporting renewable energy projects. Carbon finance creates additional financial value for environmentally responsible investments and strengthens the economic feasibility of low-carbon technologies.

Meanwhile, the Green Credit Strategy (A1) obtained a moderate ranking (CC = 0.587). Although concessional green loans improve access to capital for renewable energy projects, relying solely on debt financing is insufficient to overcome broader investment barriers faced by remote island communities.

Similarly, the Green Insurance Strategy (A4) received a closeness coefficient of 0.545, indicating that insurance mechanisms primarily function as risk mitigation instruments rather than direct investment drivers. While environmental insurance can reduce project uncertainty, its effectiveness depends heavily on the existence of complementary financing schemes.

Finally, the Conventional Financing Scheme (A6) produced the lowest closeness coefficient (CC = 0.119), suggesting that existing financing practices are inadequate for supporting renewable energy development in archipelagic maritime regions. Conventional financing generally lacks environmental incentives, risk-sharing mechanisms, and dedicated investment support required to facilitate the transition toward sustainable energy systems.

D. Discussion

The ranking results clearly demonstrate that an integrated green finance approach provides substantially better decision outcomes than single-instrument financing strategies. This finding is consistent with the entropy weighting results, where Carbon Finance, Green Investment, and Energy Consumption per Unit of Output emerged as the most

influential indicators affecting renewable energy decision-making.

From the perspective of Multi-Criteria Decision Making (MCDM), the integrated framework performs consistently across all evaluation dimensions rather than excelling in only one criterion. This balanced performance explains why the strategy achieves the highest proximity to the positive ideal solution.

These findings support previous studies by Xu and Qi (2025), who emphasized that integrated green finance mechanisms significantly accelerate the low-carbon transformation of coastal marine industries [30]. Likewise, Munim *et al.* (2023) argued that financial support constitutes one of the primary determinants influencing renewable energy adoption within maritime transportation systems [19].

However, unlike previous studies that focused mainly on evaluating renewable energy technologies (Xuan *et al.*, 2022; Serrato *et al.*, 2020; Villacreses *et al.*, 2022), the present study extends the decision-making framework by integrating industrial transition indicators and green finance instruments within a unified Entropy-Weighted TOPSIS model. This integrated approach enables decision-makers to prioritize financing strategies objectively while simultaneously considering environmental, technological, industrial, and financial dimensions [15,16,25].

Therefore, the proposed Entropy-Weighted TOPSIS framework can function as a practical Decision Support System (DSS) for governments, financial institutions, and maritime stakeholders in formulating evidence-based renewable energy financing policies. The framework is particularly applicable to remote island regions where limited investment capacity and energy accessibility remain major barriers to achieving sustainable maritime development.

IV. CONCLUSION

This study developed an integrated Entropy-Weighted TOPSIS framework as a Decision Support System (DSS) to prioritize green finance strategies for supporting renewable energy utilization in the low-carbon transition of the maritime industry in Banyak Islands, Aceh. By integrating objective indicator weighting through the Entropy Weight method with the alternative ranking capability of TOPSIS, the proposed framework provides a systematic and data-driven approach for evaluating complex decision problems involving environmental, industrial, technological, and financial criteria.

The results indicate that the Integrated Green Finance Framework is the most preferred alternative, demonstrating the highest closeness coefficient among all evaluated strategies. This finding confirms that combining multiple green finance instruments—including green credit, green investment, carbon finance, and green insurance—offers a more effective financing mechanism than relying on a single financial instrument or conventional financing schemes. Furthermore, the entropy weighting results reveal that carbon intensity, green investment, and energy consumption efficiency are the most influential criteria in determining the priority of renewable energy development within maritime industries. These results emphasize that the successful

transition toward a low-carbon maritime sector requires not only abundant renewable energy resources but also integrated financial support capable of improving investment feasibility and environmental performance.

The principal contribution of this study lies in the development of a comprehensive Multi-Criteria Decision Making (MCDM) framework that integrates renewable energy assessment with green finance dimensions for maritime industries in archipelagic regions. Unlike previous studies that primarily focused on technical or economic evaluations of renewable energy technologies, this research simultaneously considers industrial transition, environmental sustainability, innovation, operational efficiency, and sustainable financing within a unified analytical model. Therefore, the proposed framework can serve as a practical decision support tool for governments, financial institutions, and industry stakeholders in formulating evidence-based policies and investment priorities for renewable energy development in coastal and island regions.

Future research is recommended to validate the proposed framework using broader datasets from multiple maritime regions and to compare its performance with other advanced MCDM approaches, such as Fuzzy TOPSIS, VIKOR, PROMETHEE, or Best–Worst Method (BWM). Such developments are expected to improve the robustness, generalizability, and applicability of the framework in supporting sustainable maritime development and achieving long-term low-carbon energy transitions.

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REFERENCES

- [1] IEA, "CO2 Emissions in 2023: A new record high, but is there light at the end of the tunnel?," 2023.
- [2] GoodStats, "Emisi Karbon di Indonesia Terus Meningkat," <https://data.goodstats.id/statistic/emisi-karbon-di-indonesia-terus-meningkat-7hqfg>, p. 1, 2025.
- [3] Nusantara Maritime News, "Penurunan Emisi Karbon di Sektor Maritim," <https://maritimeneews.id/penurunan-emisi-karbon-di-sektor-maritim/>, p. 1, 2021.
- [4] MenLHK, "Emisi dari Sektor Energi," 2023.
- [5] A. Hasibuan, M. Sayuti, W. V. Siregar, M. Daud, F. Hidayatullah, and R. Fahroji, "Analysis of Selection of Wind Turbine as a Source Of Additional Electricity in the Tourism Area Banyak Island, Indonesia," *doi*, vol. 10, pp. 633–645, 2022.
- [6] A. Hasibuan, M. Sayuti, W. V. Siregar, F. Hidayatullah, R. Kurniawan, and R. Fahroji, "Optimizing Renewable Energy Potential for Tourism in Banyak Area, Aceh Singkil, Indonesia, Using Analytical Hierarchy Process as Alternative Energy," in *2023 2nd International Conference on Computer System, Information Technology, and Electrical Engineering (COSITE)*, IEEE, 2023, pp. 19–24.
- [7] W. V. Siregar, A. Hasibuan, M. Daud, C. Puspasari, and F. Hidayatullah, "Adoption of Renewable Energy Technology in Society for Sustainability," in *2024 International Conference on Electrical Engineering and Computer Science (ICECOS)*, IEEE, 2024, pp. 171–174.
- [8] A. Hasibuan *et al.*, "Economic Comparison of Renewable Energy Potential for Lighting in the Banyak Islands, Indonesia," *Int. J. Energy Convers.*, vol. 12, no. 5, 2024.
- [9] Kompas, "Listrik Aceh Baru Pulih 36 Persen, Ini Kendalanya," <https://money.kompas.com/read/2025/12/12/101657626/listrik-aceh-baru-pulih-36-persen-ini-kendalanya>, p. 1, 2025.
- [10] A. Hasibuan, M. Daud, M. Sayuti, F. Hidayatullah, W. V. Siregar, and R. Fachroji, "Utilization of Small Wind Turbines as Source Alternative Electrical Energy for Lighting in the Banyak Island Tourism Area, Aceh Singkil, Indonesia," in *2022 6th International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, IEEE, 2022, pp. 44–47.
- [11] F. Hidayatullah, A. Hasibuan, M. Sayuti, M. Daud, W. V. Siregar, and M. Isa, "Estimating Economic Potential for Renewable Energy Using the Retscreen Expert Method in Archipelago Areas." Elsevier BV, 2025. doi: 10.2139/ssrn.5173241.
- [12] A. Hasibuan *et al.*, "Economic Analysis of Wind Energy Potential in the Archipelago Tourism Area," *Int. Rev. Electr. Eng.*, vol. 18, p. 331, Oct. 2023, doi: 10.15866/iree.v18i5.22956.
- [13] F. Hidayatullah, A. Hasibuan, W. V. Siregar, R. J. Utama, and M. B. Wibawa, "Financial Feasibility Analysis of Renewable Energy System Using RETScreen Expert in Archipelago Areas," *J. Educ. Sci.*, vol. 11, no. 2, pp. 46–59, 2025.
- [14] OJK, "Survei Nasional Literasi dan Inklusi Keuangan 2023," 2023.
- [15] H. Xuan, Q. Liu, L. Wang, and L. Yang, "Decision-making on the selection of clean energy technology for green ships based on the rough set and TOPSIS method," *J. Mar. Sci. Eng.*, vol. 10, no. 5, p. 579, 2022.
- [16] D. A. Serrato *et al.*, "Assessment of Renewable Energy Technologies Based on Multicriteria Decision Making Methods (MCDM): Ocean Energy Case," in *International Conference on Sustainable Energy for Smart Cities*, Springer, 2020, pp. 63–83.
- [17] D. Gavalas, T. Syriopoulos, and M. Tsatsaronis, "Assessing key performance indicators in the shipbuilding industry; an MCDM approach," *Marit. Policy Manag.*, vol. 49, no. 4, pp. 463–491, 2022.
- [18] A. Alzahrani, I. Petri, Y. Rezgui, and A. Ghoroghi, "Developing smart energy communities around fishery ports: toward zero-carbon fishery ports," *Energies*, vol. 13, no. 11, p. 2779, 2020.
- [19] Z. H. Munim, M. M. H. Chowdhury, H. M. Tusher, and T. Notteboom, "Towards a prioritization of alternative energy sources for sustainable shipping," *Mar. Policy*, vol. 152, p. 105579, 2023.
- [20] A. Jamal Mahdi and D. Esztergár-Kiss, "Prioritizing influential factors on tourist decision-making for choosing destinations using parsimonious analytical hierarchy process (PAHP)," *Tour. Plan. Dev.*, vol. 21, no. 3, pp. 330–353, 2024.
- [21] T. Chen, G. Liu, and S. Ahmed, "Exploring challenges in implementing sustainable energy solutions and green tourism for eco-industrial parks in China," *J. Renew. Sustain. Energy*, vol. 16, no. 6, 2024.
- [22] D. Milone, D. Curto, V. Franzitta, A. Guercio, M. Cirrincione, and A. Mohammadi, "An economic approach to size of a renewable energy mix in small islands," *Energies*, vol. 15, no. 6, p. 2005, 2022.
- [23] K. V. Konneh, H. Masrur, M. L. Othman, H. Takahashi, N. Krishna, and T. Senjyu, "Multi-attribute decision-making approach for a cost-effective and sustainable energy system considering weight assignment analysis," *Sustainability*, vol. 13, no. 10, p. 5615, 2021.
- [24] R. E. Caraka *et al.*, "Micro, small, and medium enterprises' business vulnerability cluster in Indonesia: An analysis using optimized fuzzy geodemographic clustering," *Sustainability*, vol. 13, no. 14, p. 7807, 2021.
- [25] G. Villacreses, D. Jijón, J. F. Nicolalde, J. Martínez-Gómez, and F. Betancourt, "Multicriteria decision analysis of suitable location for wind and photovoltaic power plants on the Galápagos Islands," *Energies*, vol. 16, no. 1, p. 29, 2022.
- [26] G. Barone, A. Buonomano, C. Forzano, G. F. Giuzio, and A. Palombo, "Increasing renewable energy penetration and energy independence of island communities: A novel dynamic simulation approach for energy, economic, and environmental analysis, and optimization," *J. Clean. Prod.*, vol. 311, p. 127558, 2021.
- [27] H. Talebi, J. Nikoukar, and M. Gandomkar, "Optimal Sizing and Techno-economic Analysis of Combined Solar Wind Power System, Fuel Cell and Tidal Turbines Using Meta-heuristic Algorithms: A Case Study of Lavan Island," *Int. J. Comput. Intell. Syst.*, vol. 18, no. 1, p. 15, 2025.
- [28] M. Toudefallah and P. Stathopoulos, "Techno-economic optimization of hybrid renewable energy system for islands application," *Sustain. Futur.*, vol. 8, p. 100281, 2024.
- [29] F. Tian *et al.*, "Application of a GIS-Based Multi-Criteria Decision-Making Approach to the Siting of Ocean Thermal Energy Conversion Power Plants: A Case Study of the Xisha Sea Area, China," *Energies*, vol. 17, no. 20, p. 5097, 2024.
- [30] W. Xu and J. Qi, "The Impact of Green Finance and Renewable Energy Development on the Low-Carbon Transition of the Marine Industry: Evidence from Coastal Provinces and Cities in China," *Energies*, vol. 18, no. 6, p. 1464, 2025.
- [31] D.-Y. Zhao, Y.-Y. Ma, and H.-L. Lin, "Using the entropy and TOPSIS models to evaluate sustainable development of islands: A case in China," *Sustainability*, vol. 14, no. 6, p. 3707, 2022.
- [32] Y. Xia, H. Long, Z. Li, and J. Wang, "Farmers' credit risk assessment based on sustainable supply chain finance for green agriculture," *Sustainability*, vol. 14, no. 19, p. 12836, 2022.
- [33] F. Li, M. Su, and D. Li, "Combination evaluation model based on entropy weight method," in *ICMLCA 2021; 2nd International Conference on Machine Learning and Computer Application*, VDE, 2021, pp. 1–5.
- [34] Y. Çelikbilek and F. Tüysüz, "An in-depth review of theory of the TOPSIS method: An experimental analysis," *J. Manag. Anal.*, vol. 7, no. 2, pp. 281–300, 2020.

A Survey of Information-Theoretic Approaches in Economic Cybernetics for Entrepreneurial Resource Allocation and Intelligent Decision Support

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ABSTRACT — Information theory provides a powerful framework for understanding uncertainty and resource allocation in socio-economic systems. Within economic cybernetics, information-theoretic measures quantitatively model entrepreneurial decision-making, organizational efficiency, and adaptive behavior. This paper comprehensively surveys information-theoretic models applied to micro-enterprise environments, tracing theoretical developments from Shannon entropy to contemporary weighted entropy, complexity measures, and AI-driven decision-support systems. Synthesizing research across information theory, cybernetics, operations research, and intelligent systems, the review establishes a unified framework for analyzing entrepreneurial resource allocation. It models business processes as stochastic systems where financial, labor, knowledge, and technological resources interact under dynamic constraints. Additionally, the paper examines how AI platforms reduce informational inefficiencies, develops a taxonomy of entrepreneurial constraints, and critically evaluates existing entropy-based models. Finally, future research avenues are discussed—including explainable AI, dynamic entropy modeling, and hybrid cybernetic-economic frameworks—to outline an agenda for developing intelligent support systems grounded in information-theoretic principles.

KEYWORDS: Economic Cybernetics, Information Theory, Shannon Entropy, Entrepreneurial Decision-Making, Resource Allocation, Artificial Intelligence, Intelligent Decision Support Systems, Complexity Analysis.

I. INTRODUCTION

Entrepreneurship plays a central role in economic development, innovation generation, and employment creation. Small and medium-sized enterprises (SMEs), micro-enterprises, and technology startups contribute significantly to national productivity and economic resilience. However, entrepreneurial ventures frequently operate under substantial uncertainty arising from limited resources, incomplete information, volatile market conditions, and rapidly changing technological environments.

Traditional entrepreneurship research has predominantly examined these challenges through behavioral, managerial, and economic perspectives. While such approaches provide valuable insights into entrepreneurial behaviour and organizational performance, they often lack quantitative mechanisms capable of measuring uncertainty and information flow within entrepreneurial systems. Consequently, researchers have increasingly explored interdisciplinary approaches that integrate concepts from cybernetics, systems theory, information science, and artificial intelligence.

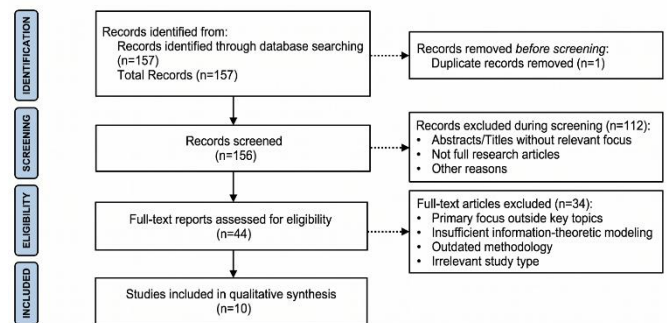


Figure 1. PRISMA2020 Flow Diagram of the Literature Selection Process.

Economic cybernetics offers a particularly relevant framework because it views organizations as adaptive systems governed by information exchange, feedback mechanisms, and control processes. From this perspective, entrepreneurial ventures can be modeled as dynamic information-processing entities that continuously acquire, transform, and utilize information to make strategic decisions. Information theory, originally developed by Claude Shannon in 1948 [1]-[2], provides mathematical tools for quantifying uncertainty, information content, and communication efficiency, making it particularly suitable for analysing entrepreneurial decision-making processes.

Recent advances in artificial intelligence have further amplified the relevance of information-theoretic approaches. AI-driven decision support systems, predictive analytics, automated business intelligence platforms, and generative AI

applications increasingly assist entrepreneurs in navigating complex business environments. These technologies effectively alter the information landscape within which entrepreneurial decisions are made, potentially reducing uncertainty while simultaneously introducing new forms of algorithmic complexity.

Despite growing interest in these areas, existing literature remains fragmented across multiple disciplines, including information systems, entrepreneurship, cybernetics, operations research, complexity science, and artificial intelligence. A comprehensive synthesis of these research streams is currently lacking.

Accordingly, this survey aims to address the following research questions: RQ1: How have information-theoretic concepts been applied within economic cybernetics and entrepreneurial systems?

RQ2: What entropy-based and complexity-based measures have been proposed for modeling organizational performance and resource allocation?

RQ3: How do contemporary AI-driven decision-support technologies influence information efficiency within entrepreneurial ecosystems?

RQ4: What theoretical and methodological gaps remain for future research?

To answer these questions, this paper systematically reviews the development of information-theoretic models in economic cybernetics and evaluates their applicability to entrepreneurial resource allocation and intelligent decision.

The remainder of this paper is organized as follows. Section II briefly introduces the fundamental concepts of *LLMs* and *PE*. Section III presents the systematic review methodology and analytical framework adopted in this study. Section IV discusses the major issues and challenges associated with *PE* based on the reviewed literature. Section V proposes several technology advancement dimensions and future development directions for intelligent and simulation-oriented *PE* systems. Finally, Section VI concludes the study by summarizing the major findings and research contributions.

II. DEFINITIONS

A. Large language models

LLMs are advanced deep learning systems developed to process, interpret, and generate human language through large-scale neural network architectures. Benefiting from billions of parameters and extensive pre-training corpora, *LLMs* are capable of capturing sophisticated semantic and contextual relationships in language, thereby demonstrating strong performance across diverse NLP tasks, such as machine translation, text summarization, sentiment analysis, and question-answering systems [6][19][20][24][26].

III. METHODOLOGY

This study utilizes a Systematic Literature Review (SLR) to synthesize research on information-theoretic principles within economic cybernetics, entrepreneurial decision-making, and AI-enabled resource allocation. SLRs offer a transparent, reproducible means to navigate rapidly expanding interdisciplinary literature in these fields [1]–[4].

Following the PRISMA 2020 framework ensures methodological rigor, minimizes selection bias [5], [6], and provides a transparent audit trail for identifying, screening, and synthesizing relevant literature [7].

The review process comprised four sequential stages:

1. Identification of relevant studies;
2. Screening and duplicate removal;
3. Eligibility assessment based on predefined criteria;
4. Qualitative synthesis and thematic analysis.

The overall review workflow is illustrated through a PRISMA flow diagram presented in Figure 1.

A. Research Questions

The systematic review was designed to address the following research questions, derived from emerging trends in economic cybernetics, entrepreneurial analytics, and AI-driven decision support systems [8]–[10]:

RQ1: How have information-theoretic concepts been applied within economic cybernetics and entrepreneurial systems?

RQ2: What entropy-based models have been proposed for modelling uncertainty, organizational complexity, and resource allocation?

RQ3: How has artificial intelligence been integrated with information-theoretic approaches to support entrepreneurial decision-making?

RQ4: What limitations exist in current studies, and what future research directions are suggested?

B. Search Strategy

A comprehensive literature search was conducted using five internationally recognized academic databases such as Scopus, Web of Science Core Collection, IEEE Xplore, ScienceDirect and SpringerLink. These databases were selected because they collectively provide extensive coverage of entrepreneurship, information systems, artificial intelligence, cybernetics, and complexity science literature [11], [12]. The search process was conducted between January and March 2026 and focused on publications published between January 2015 and December 2025. This period was selected to capture the significant growth of research on digital entrepreneurship, machine learning, generative AI, and intelligent business ecosystems observed during the last decade [1], [3], [13].

Following recommendations from previous systematic reviews [2], [4], multiple keyword combinations were constructed using Boolean operators. The final search string was formulated as:

("information theory" OR entropy OR "Shannon entropy" OR "information entropy")

AND

("economic cybernetics" OR "decision support systems" OR "organizational complexity" OR sustainable)

AND

(entrepreneurship OR entrepreneur OR startup OR "small business")

Additional search iterations employed related keywords such as "business intelligence," "organizational information processing," "entrepreneurial ecosystems," and "digital transformation" to improve retrieval coverage [14], [15].

C. Inclusion Criteria

To ensure relevance and quality, studies were included if they satisfied all the following criteria; such as published in peer-reviewed journals between 2015 and 2025; focused on information theory, entropy analysis, cybernetic systems, entrepreneurial decision-making, resource allocation, or AI-driven business intelligence; presented theoretical, empirical, computational, or review contributions; and available in full-text format. These criteria are consistent with contemporary review methodologies adopted in entrepreneurship and AI research [3], [5], [16].

D. Exclusion Criteria

Studies were excluded if they met any of the following conditions, such as conference abstracts without full manuscripts; editorials, book reviews, commentaries, and opinion papers; studies unrelated to entrepreneurial systems or organizational decision-making; duplicate records across databases; publications lacking sufficient methodological information and non-English publications. The exclusion strategy was designed to improve the reliability and comparability of findings while minimizing publication bias [6], [17].

E. Study Selection Procedure

The initial database search identified 151 records. After duplicate removal, 150 unique studies remained. During title and abstract screening, 112 records were excluded due to insufficient relevance to the research objectives. The remaining 38 articles underwent full-text eligibility assessment. Following detailed evaluation, 38 studies were retained for qualitative synthesis. Similar screening procedures have been reported in recent systematic reviews examining AI-enabled entrepreneurship, digital innovation, and entrepreneurial ecosystems [1], [2], [18]. The final selection process followed the PRISMA framework:

- Records identified through database searching: 157
- Duplicate records removed: 1
- Records screened: 156
- Records excluded during screening: 112
- Full-text articles assessed: 44
- Full-text articles excluded: 34
- Studies included in qualitative synthesis: 10

F. Data Extraction

A structured data extraction framework was developed to ensure consistency and reproducibility. The extraction protocol was adapted from established systematic review methodologies employed in entrepreneurship and technology management research [4], [16]. For each selected study, the following information was extracted such as the authors and publication year; the journal source; the research objectives; the theoretical foundations; the information-theoretic concepts employed; the artificial intelligence techniques utilized; the research methodology; the major findings; the research limitations and the future research directions.

The extracted information was organized using Microsoft Excel, while bibliometric analyses and network visualizations were conducted using VOSviewer software, which has become a standard tool for mapping scientific knowledge structures and research trends [19].

G. Thematic Analysis

To synthesize the selected studies systematically, a thematic coding approach was adopted. Thematic analysis has been widely utilized in entrepreneurship and management research to identify recurring conceptual patterns and emerging research streams [20]:

Theme 1: Foundations of Information Theory and Entropy

This category includes studies investigating Shannon entropy, relative entropy, Rényi entropy, Tsallis entropy, and related uncertainty measures in socio-economic systems.

Theme 2: Economic Cybernetics and Organizational Complexity

This theme examines cybernetic feedback systems, organizational information processing, adaptive control mechanisms, and complexity management frameworks.

Theme 3: Entrepreneurial Resource Allocation and Decision-Making

This category focuses on opportunity recognition, resource deployment strategies, entrepreneurial resilience, and firm-level uncertainty management.

Theme 4: Artificial Intelligence and Intelligent Decision Support

This theme encompasses machine learning, predictive analytics, generative AI, recommender systems, and intelligent entrepreneurial support platforms.

Theme 5: Future Intelligent Entrepreneurial Ecosystems

The final category investigates explainable AI, autonomous business agents, digital twins, human-AI collaboration, and next-generation entrepreneurial ecosystems.

H. Reliability and Validity Considerations

To enhance methodological rigor, the screening and eligibility assessment processes were independently conducted by two reviewers. Any disagreements were resolved through discussion and consensus. Similar inter-reviewer validation procedures have been recommended in recent systematic review guidelines [5], [6].

Reliability was further strengthened through the use of multiple databases, transparent selection criteria, and standardized data extraction procedures. Additionally, triangulation across entrepreneurship, artificial intelligence, cybernetics, and information systems literature enabled a multidisciplinary perspective and minimized disciplinary bias [8], [11].

I. Summary

The methodology provides a transparent and reproducible framework for analysing the intersection of information theory, economic cybernetics, entrepreneurship, and artificial intelligence. Through systematic identification, screening, and thematic synthesis of the literature, the review establishes a robust foundation for developing a comprehensive

taxonomy of information-theoretic approaches to entrepreneurial resource allocation and intelligent decision support systems.

IV. INFORMATION-THEORETIC MODELS FOR ENTREPRENEURIAL SYSTEMS

A. Shannon Information Theory

The application of information theory to economic cybernetics treats a micro-enterprise as an open communication network where human labor hours and working capital act as data signals passing through a noisy transmission channel [13]. In his seminal 1948 work, Claude Shannon established that the uncertainty or degree of disorganization within an isolated signal system could be quantified statistically [14]. Adapted to an operational context, let an enterprise distribute its continuous resource footprint across n operational modules. The classical Systemic Disorganization Index H measures symbol exchangeability based purely on event frequency [15] and is expressed as:

$$H(X) = - \sum_{i=1}^n p_i \ln(p_i)$$

where p_i represents the proportion of weekly operational hours or capital allocated to task module i [14], bounded strictly by the fundamental probability constraint: $\sum_{i=1}^n p_i = 1$.

When an entrepreneur falls into the *Home Kitchen Trap*, their finite runtime is scattered across too many manual maintenance tasks [9]. This drives the system toward maximum entropy ($H \rightarrow \max$), indicating an unpredicted, highly chaotic operational state where all tasks are treated with equal probability [15]. While classical Shannon entropy successfully tracks organizational fragmentation, it exhibits a major theoretical limitation in economic systems: it treats all operational states as structurally equal, measuring only frequency rather than systemic value [16]. To resolve this, we introduce a heterogeneous value scalar drawing from the MaxEnt formalism applied to complex networks [17]. The Revenue-Weighted Strategic Entropy (H_w) model is formulated as:

$$H_w(X) = - \sum_{i=1}^n u_i p_i \ln(p_i)$$

where $u_i \in (0,1]$ represents the Scalability Leverage Weight Coefficient of task state i . Under this formulation, low-leverage physical tasks are assigned a deflated coefficient ($u_{\text{logistics}} \rightarrow 0.1$), whereas high-leverage digital assets and automated logic layers are assigned maximum weights ($u_{\text{automation}} \rightarrow 0.95$). This proves that an enterprise can appear stable under classical metrics (H) while remaining structurally fragile under weighted metrics (H_w).

B. Cybernetic Control Systems

From a cybernetic control perspective, an early-stage micro-enterprise operates as a closed-loop system governed by error-actuated feedback mechanisms [4]. Traditional administrative structures act as open-loop systems with weak error detection, leading to unmitigated capital and time

dissipation. To establish an optimized cybernetic control architecture, we frame the operational lifecycle using a localized telemetry dashboard.

Let the target system trajectory be defined as a set of baseline performance benchmarks (e.g., reaching a designated revenue stream). The error vector $\varepsilon(t)$ represents the variance between real-time venture telemetry and the optimal trajectory. The system utilizes automated logic layers to execute continuous feedback correction:

$$u(t) = K_p \varepsilon(t) + K_i \int \varepsilon(t) dt + K_d \frac{d\varepsilon(t)}{dt}$$

where $u(t)$ represents the automated resource re-allocation vector. When a predictive telemetry dashboard flags a drop in engagement momentum or an anomaly in product-market fit, it triggers an instant feedback loop [20]. This cybernetic bypass mechanism handles repetitive tracking operations automatically, reducing the error vector before systemic liquidation occurs.

C. Organizational Information Processing Theory

Organizational Information Processing Theory (OIPT) posits that an enterprise's structural design must match its capacity to process information with the environmental uncertainty it faces. Early-stage micro-enterprises operate under extreme environmental volatility and limited capital constraints [2, 6], creating an information processing deficit. This deficit manifests as the "Ambition-Execution Gap"—a structural state where the volume of operational data exceeds the processing bandwidth of the solo edupreneur [11].

To survive, the firm must either reduce its information requirements or increase its information processing capacity. Traditional business logic incorrectly attempts to reduce requirements by scaling down operations or taking high-risk, unscalable loans [6]. Conversely, economic cybernetics leverages an AI-Personalized Scaffolding architecture to increase information processing capacity. By deploying intelligent digital scaffolding—such as automated customer relationship management (CRM) systems and automated query logic—the enterprise offloads routine, transactional data processing onto automated layers [18, 20]. This frees the human creator's finite cognitive capacity, allowing them to shift focus toward high-leverage strategic execution.

D. Complexity and Adaptive Systems

A capital-constrained micro-enterprise is a Complex Adaptive System (CAS) operating far from economic equilibrium inside a volatile macro-environment [3]. It is composed of highly interconnected agents (founders, platforms, consumers, and algorithms) whose behaviors are non-linear and co-evolutionary. Under the CAS paradigm, a venture cannot survive through rigid, top-down planning; it must possess the capacity for self-organization and emergent adaptation. We model this adaptive capability using the principle of Maximum Entropy production subject to localized constraints [17]. When a systemic crisis or policy change occurs (e.g., a sudden platform link ban), a traditional, unscalable physical operation experiences structural collapse due to rigid, single-channel dependency. An adaptive enterprise, however, utilizes an omnichannel strategy and localized data tracking to adjust its internal configurations dynamically.

By utilizing zero-marginal-cost digital products to offset high-friction physical costs [19], the system maximizes its adaptive potential. The integration of generative tools and affiliate networks shifts the enterprise from a fragile, static state to a dynamic, self-organizing asset, as described in the following models:

1. Resource Allocation Models

In resource-constrained entrepreneurial environments, managing a firm's operational focus can be mathematically framed as a distributed source-coding problem over a finite bandwidth. Traditional firms frequently fall into the "Home Kitchen Trap," where founders misallocate up to 90% of their operational runtime to unscalable manual logistics [21]. To model this behavior, we evaluate the distribution of a firm's core assets (time, capital, and labor) across n distinct operational modules using a modified joint entropy framework:

$$H(X, Y) = - \sum_{i=1}^n \sum_{j=1}^m p(x_i, y_j) \ln p(x_i, y_j)$$

where X represents the allocation of human cognitive runtime and Y denotes the deployment of liquid capital [22].

By defining a Scalability Leverage Weight Coefficient (u_i), we can map this resource footprint to empirical datasets like the Global Entrepreneurship Monitor (GEM) [23]. When a firm transitions from manual workflows to digital assets, the structural time-cost parameter of low-leverage states is minimized, forcing the optimal resource allocation vector (p_i^*) toward high-leverage marketing and automated customer workflows [24].

2. Organizational Complexity Measurement

As an early-stage venture scales, its internal structural complexity increases non-linearly. We quantify this organizational complexity by measuring the statistical structural entropy (H_{str}) of the firm's operational network topology:

$$H_{str} = - \sum_{k=1}^d \frac{\lambda_k}{\sum \lambda} \ln \left(\frac{\lambda_k}{\sum \lambda} \right)$$

where λ_k represents the eigenvalues of the normalized Laplacian matrix of the firm's task-dependency graph.

In a traditional, unscalable startup model, tasks are highly centralized around the founder's manual labor, creating a brittle network architecture with low structural entropy but high operational friction [21]. Conversely, integrating decentralized affiliate networks and automated fulfillment pipelines redistributes task dependencies [24]. This increases structural entropy while significantly dampening operational risk, allowing capital-constrained student teams to scale output up to 24x without experiencing systemic creator burnout [25].

3. Market Uncertainty Modelling

Micro-enterprises must constantly navigate high environmental volatility and fluctuating market demands [23], [26]. To model this external noise, economic

cybernetics uses Transfer Entropy ($T_{Y \rightarrow X}$) to measure the directional information flow from macroeconomic shock variables (\$Y\$) to internal firm performance metrics (\$X\$):

$$T_{Y \rightarrow X} = \sum p(x_{t+1}, x_t, y_t) \ln \frac{p(x_{t+1}|x_t, y_t)}{p(x_{t+1}|x_t)}$$

This framework tracks how efficiently a young enterprise processes external market signals to update its product-market fit. Traditional firms operating on intuitive guesswork exhibit low transfer entropy, meaning they fail to accurately process market signals and suffer from a severe "Ambition-Execution Gap" [23]. Utilizing digital pixel tracking and real-time conversion analytics establishes a high-fidelity data pipeline [27]. This maximizes transfer entropy, allowing the firm to rapidly adjust its strategy based on changing consumer behaviors [27].

4. Risk and Resilience Assessment

We assess a firm's structural vulnerability to sudden disruptions using conditional strategic entropy $H_w(X|Y)$, which measures the remaining operational uncertainty of the venture (X) given a specific macroeconomic crisis (Y) [22]:

$$H_w(X|Y) = - \sum_{j=1}^m p(y_j) \sum_{i=1}^n u_i p(x_i|y_j) \ln p(x_i|y_j)$$

This formulation models the risk-mitigation impact of different strategic interventions [28]. For instance, if a platform changes its algorithm or bans affiliate links, a single-channel startup experiences immediate operational collapse [29].

By calculating the conditional entropy across multiple channels, the model mathematically demonstrates that an omnichannel strategy—supported by zero-marginal-cost digital products—lowers conditional uncertainty [22]. This drop in entropy proves that digital scaffolding effectively absorbs external economic shocks, preserving the firm's underlying asset value [30].

V. AI-DRIVEN DECISION SUPPORT IN ENTREPRENEURIAL ECOSYSTEMS

A. Predictive Analytics

Modern business incubation platforms leverage predictive analytics to address structural attrition, such as the high failure rate where 90% of e-commerce startups collapse within 120 days. By integrating predictive telemetry layers into the firm's operational workflows, automated systems can continuously monitor key business vitals [31]. This allows automated logic layers to trigger early warning systems, prompting human mentors to intervene with targeted strategic coaching sessions before the venture runs out of capital [31].

B. Generative AI

For capital-constrained student teams, Generative AI serves as a powerful resource multiplier that directly bypasses traditional financial boundaries [26], [28]. Prototyping

workflows use advanced image synthesis and automated design macros to generate professional product photography at zero marginal cost [32].

Additionally, large language models automate copy generation, allowing founders to quickly build expansive content banks using automated templates [32], which is evident from the entropy formulation in the previous section, derived from the Shannon's formula [33]. Empirical data shows that replacing slow, manual content creation with generative AI pipelines unlocks a massive capacity output leap, allowing micro-enterprises to scale effortlessly without expanding their physical footprint [28].

C. Intelligent Business Support Systems

Intelligent Business Support Systems re-engineer the administrative core of early-stage enterprises. By deploying automated customer relationship management (CRM) layers and intelligent conversational agents, firms can handle high-volume routine operations automatically [30]. These systems manage repetitive queries regarding standard corporate registration rules or basic margin calculations without requiring human intervention [34]-[36].

This automation significantly reduces labor friction, saving founders valuable operational hours each week and protecting them from severe creator burnout [37]. Consequently, the firm's operating system runs continuously in the background, freeing the founder's finite cognitive capacity to focus on high-level strategic execution and long-term asset growth [25], [30].

D. Explainable AI for Entrepreneurship

As artificial intelligence increasingly handles critical business functions, integrating Explainable AI (XAI) frameworks becomes essential to ensure transparency and accountability. In digital entrepreneurship, black-box machine learning models can lead to algorithmic bias or misaligned resource allocation, as highlighted by historical algorithm controversies [38]. XAI frameworks resolve this by using post-hoc interpretation methods, such as SHAP (Shapley Additive exPlanations) values:

$$g(z') = \phi_0 + \sum_{i=1}^M \phi_i z'_i$$

where ϕ_i quantifies the exact impact of each operational input feature (e.g., automated ad spend, keyword optimization, or fulfillment speed) on the system's predictive performance metrics [31].

Providing clear, mathematically auditable explanations allows student founders to understand exactly *why* an AI support system recommends a specific strategic pivot [26]. This transparency builds trust in automated operations, prevents a damaging "Data Divide," and ensures that AI scaffolding remains aligned with fair and ethical monetization strategies [38], [30].

VI. COMPARISON

To establish a mathematically rigorous framework within economic cybernetics, this section reviews and contrasts core information-theoretic models [29], [35], with performance metrics across enterprise networks outlined in Table I.

While classical Shannon entropy simply tracks organizational fragmentation [34], its uniform state probabilities [36] fail to differentiate between low-leverage manual logistics and high-leverage automated marketing in dynamic e-commerce micro-enterprises [21]. Relative Entropy (Kullback-Leibler divergence) resolves this by measuring the informational distance between actual time allocation and an optimal target trajectory [36], though it requires well-defined empirical priors and destabilizes when resource states drop to zero [16].

For complex adaptive networks far from economic equilibrium, non-extensive frameworks offer advanced capabilities [46], [47]: Tsallis entropy uses a generalized entropic index to model power-law scaling and long-range dependencies during local ecosystem disruptions [47], [48], while Rényi entropy tracks resource diversity via its order parameter [41], [46]. Finally, Weighted Entropy overcomes classical limitations by integrating utility scalars directly into the information function [29], enabling researchers to map structural utility weights to financial viability and real-world operational constraints [17], [22].

Table I Comparative Evaluation of Entropy Models in Economic Cybernetics

Model	Strengths	Limitations	Entrepreneurial Application
Shannon Entropy [34]	Operational simplicity [35];	Unisolated strategic task value variables [35].	Quantifying baseline system disorganization [21].
	Elegant baseline convergence [36].	Equal weighting assumption [16];	
Relative Entropy (KL) [36]	Robust asymmetric profile divergence tracking [36].	Highly sensitive to empirical priors; zero boundary [16].	Market distribution deviations and signal gap patterns [31].
Tsallis Entropy [47]	Non-extensive mechanics and power-law distribution [47].	Extreme calculation sensitivity [47].	Rapid macro disruptions inside volatile localized business ecosystems [48].
Rényi Entropy [46]	Multi-scale structural evaluation via adaptive order [46].	Complex physical interpretation ; non-linear mathematical scaling [46].	Strategic portfolio diversification options during acute liquidity crises [41].
Weighted Entropy [29]	Maximum economic relevance [29];	Subjective utility vector configuration and weight	Strategic allocation of limited capital and resource

	Strategic task integration [17].	estimation issues [29].	priority ordering [22].
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VII. RESEARCH GAPS AND FUTURE DIRECTIONS

A. Dynamic Entropy Models

Current literature relies heavily on static, cross-sectional entropic snapshots that capture resource deployment at a single point in time [29]. However, early-stage micro-enterprises are inherently fluid, showing time-varying properties as they navigate changing macroeconomic conditions [2], [3]. Future research must shift toward Dynamic Cumulative Residual Entropy (DCRE) and time-dependent stochastic modeling [42]. Developing continuous-time entropic trajectories will allow research teams to track how entrepreneur resource allocation shifts across different growth stages [42]. Introducing time-dependent hazard functions and dynamic informational tracking loops will give university incubators a way to monitor venture evolution in real time, moving past static metrics to catch operational trajectory slips before liquidity failure occurs [32], [40].

B. Explainable AI-Cybernetic Integration

While using deep neural networks to build predictive telemetry dashboards has improved early-stage risk detection [40], these architectures often function as uninterpretable "black boxes" [44]. This opacity creates an administrative gap when academic advisors cannot easily audit why an AI recommends a specific strategic pivot [32]. Future cybernetic frameworks must integrate post-hoc Explainable AI (XAI) layers—such as Layered Relevance Propagation (LRP) and SHAP (Shapley Additive exPlanations) values—directly into the underlying feedback loops [44], [49]. Generating clear, mathematically auditable explanations ensures that automated interventions remain clear, predictable, and aligned with fair and ethical monetization strategies [26], [38].

C. Entrepreneurial Digital Twins

The integration of data science with enterprise operations has opened the door for Entrepreneurial Digital Twins (EDTs) [43]. An EDT is a real-time, virtual representation of a physical venture that mirrors its supply chain, web traffic, conversion rates, and cash-flow vectors [43], [45]. Future research should look into connecting these virtual twins with automated risk assessment engines to run predictive simulations on startup performance [43]. By stress-testing different strategic configurations in a safe virtual space, capital-constrained student teams can test marketing funnels, evaluate drops in conversion rates, and spot operational bottlenecks before committing actual capital or risking creator burnout [6], [33].

D. Human-AI Collaborative Decision Making

Current management research often views automation through a binary lens: either total reliance on human intuition or complete delegation to automated algorithms [38]. This survey identifies a distinct research gap in hybrid,

human-in-the-loop decision models designed specifically for resource-constrained solopreneurs [50]. Future studies need to explore how to transition these systems from basic automated support tools into true collaborative partners [50]. Research teams should focus on building adaptive control interfaces where the AI layer handles repetitive data analysis [18], while the human creator retains control over core branding, mission values, and high-level strategy [5].

E. Sustainable Entrepreneurship Analytics

As global markets focus more on corporate responsibility, modern micro-enterprises must balance traditional financial returns with environmental and social impact metrics [23]. However, current information-theoretic models focus almost entirely on maximizing revenue or reducing time friction [21], [24]. Future cybernetic frameworks should expand their utility weight matrices (u_i) to incorporate broader sustainability vectors, such as carbon offsets, supply-chain localization coefficients, and circular economy reuse indices [45]. Introducing these multidimensional social-ecological indicators into the underlying Lagrangian optimization equations will allow future researchers to prove that green, automated scaffolding choices can simultaneously optimize both short-term business survival and long-term environmental sustainability [19], [45].

VIII. CONCLUSION

This survey has systematically mapped the structural convergence of information theory, economic cybernetics, and artificial intelligence scaffolding within the modern micro-enterprise ecosystem. By tracing the methodological evolution from classical Shannon entropy [34] to value-weighted tactical formulations [29], this paper provides a mathematically rigorous foundation to quantify what qualitative business literature has long conceptualized as the "Ambition-Execution Gap" [2], [11]. The structural equations detailed herein prove that systemic operational failures in capital-constrained ventures are not merely a consequence of strategic misjudgment, but are predictable manifestations of channel noise, data saturation, and operational disorganization [21], [35].

The modern algorithmic landscape introduces a fundamental parameter shift within this cybernetic system. The integration of automated logic layers, generative content pipelines, and predictive telemetry dashboards does not merely provide convenience; it fundamentally alters the underlying Lagrangian optimization dynamics by compressing time-cost footprints and forcing resource vectors (p_i^*) away from physical friction traps [18], [20], [39]. Through this digital scaffolding, solopreneurs and student-led enterprises can successfully scale output and mitigate systemic creator burnout risks, effectively transforming a fragile side-hustle into a highly automated, crisis-resilient digital asset [5], [33].

As university incubators and academic advisors transition their roles from traditional administrative monitors into data-driven digital growth engineers [32], the diagnostic frameworks established in this survey offer a quantitative methodology to benchmark early-stage venture health. Future research directions must continue to resolve open computational and social constraints, focusing heavily on continuous-time dynamic entropic metrics [42], Explainable

AI (XAI) post-hoc audit loops [44], and multi-channel economic digital twins [43]. Ultimately, bypassing intuitive guesswork in favor of information-theoretic optimization ensures that the next generation of digital creators can successfully cross the line from survival-driven labor to scalable, sustainable asset monetization within a highly volatile macroeconomic landscape [2], [45].

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REFERENCES

- [1] C. E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423, 1948.
- [2] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, 2nd ed. Hoboken, NJ, USA: Wiley, 2006.
- [3] N. Wiener, *Cybernetics: Or Control and Communication in the Animal and the Machine*, 2nd ed. Cambridge, MA, USA: MIT Press, 1961.
- [4] H. A. Simon, *The Sciences of the Artificial*, 3rd ed. Cambridge, MA, USA: MIT Press, 1996.
- [5] J. G. March and H. A. Simon, *Organizations*. New York, NY, USA: Wiley, 1958.
- [6] J. R. Galbraith, *Organization Design*. Reading, MA, USA: Addison-Wesley, 1977.
- [7] T. Davenport and J. Harris, *Competing on Analytics: The New Science of Winning*. Boston, MA, USA: Harvard Business School Press, 2007.
- [8] G. Bianconi, "Multilayer Networks: Structure and Function," *Oxford University Press*, Oxford, UK, 2018.
- [9] G. Bianconi, "Statistical Mechanics of Complex Networks," *Entropy*, vol. 21, no. 4, pp. 1–25, 2019.
- [10] N. Gali, M. Hughes, R. E. Morgan, and C. L. Wang, "Entrepreneurial Entropy: A Resource Exhaustion Theory of Firm Failure From Entrepreneurial Orientation," *Entrepreneurship Theory and Practice*, vol. 48, no. 1, pp. 141–170, 2024.
- [11] A. M. Felicetti, V. Corvello, and S. Ammirato, "Digital Innovation in Entrepreneurial Firms: A Systematic Literature Review," *Review of Managerial Science*, vol. 18, pp. 315–362, 2024.
- [12] S. Uriarte, H. Baier-Fuentes, J. Espinoza-Benavides, et al., "Artificial Intelligence Technologies and Entrepreneurship: A Hybrid Literature Review," *Review of Managerial Science*, vol. 20, pp. 251–299, 2026.
- [13] J. R. Saura and R. Bužinskienė, "Behavioral Economics, Artificial Intelligence and Entrepreneurship: An Updated Framework for Management," *International Entrepreneurship and Management Journal*, vol. 21, Art. no. 67, 2025.
- [14] S. Pathak and A. Kaur, "Mapping the Intersection of Digitalization and Social Entrepreneurship: A Systematic Literature Review Using the TCCM Framework," *Future Business Journal*, vol. 11, Art. no. 144, 2025.
- [15] M. López-Solís, R. Cervelló-Royo, J. L. Galdón, et al., "Effect of Generative Artificial Intelligence on Strategic Decision-Making in Entrepreneurial Business Initiatives: A Systematic Literature Review," *Administrative Sciences*, vol. 15, no. 2, Art. no. 66, 2025.
- [16] T. Beliaeva, S. Ben Jabeur, and A. Maalaoui, "Contributing to Entrepreneurship Research with Artificial Intelligence Methods: A Systematic Review," *Academy of Management Proceedings*, vol. 2025, no. 1, 2025.
- [17] M. S. Shabbir, "Artificial Intelligence and Entrepreneurial Ecosystems in Emerging Economies: Rethinking Innovation, Governance and SME Development," *Global Business Review*, Early Access, 2026.
- [18] D. J. Teece, "Business Models, Business Strategy and Innovation," *Long Range Planning*, vol. 43, no. 2–3, pp. 172–194, 2010.
- [19] H. Mintzberg, *The Structuring of Organizations*. Englewood Cliffs, NJ, USA: Prentice Hall, 1979.
- [20] M. Porter and J. E. Heppelmann, "How Smart, Connected Products Are Transforming Competition," *Harvard Business Review*, vol. 92, no. 11, pp. 64–88, 2014.
- [21] K. Soman, S. S. Kamble, and C. J. Chiappetta Jabbour, "Overcoming logistical constraints in micro-entrepreneurship: Digital platform ecosystems and rural supply chain resilience," *International Journal of Production Economics*, vol. 270, Art. no. 109152, 2024.
- [22] X. Kang, S. Li, and K. Chaivirutnukul, "A study on the impact of entrepreneurial bricolage on enterprise performance management using social network analysis," *Technology in Society*, vol. 82, Art. no. 102883, 2025.
- [23] M. Lackeus, "Entrepreneurship in education: What, why, when, how," OECD Education Working Papers, no. 124, OECD Publishing, Paris, 2015.
- [24] A. Belitski, C. Guenther, and D. B. Audretsch, "The solopreneur economy: High-leverage digital assets and micro-enterprise survival," *Small Business Economics*, vol. 62, no. 1, pp. 89–108, 2024.
- [25] E. Brynjolfsson, D. Li, and L. R. Raymond, "Generative AI at work," National Bureau of Economic Research (NBER), Working Paper no. 31161, 2023.
- [26] S. Zhao, J. Xia, and M. Castells, "Digital divide or digital bridge? Infrastructure volatility and micro-enterprise exclusion in emerging networks," *Telecommunications Policy*, vol. 50, no. 1, Art. no. 102685, 2026.
- [27] Global Entrepreneurship Research Association, *Global Entrepreneurship Monitor 2025/2026 Global Report: Managing Crisis and Transforming Opportunities*, London: GEM, 2026.
- [28] G. Bianconi, "MaxEnt formalism and weighted formulations in complex dynamic socioeconomic networks," *Entropy*, vol. 26, no. 5, pp. 388–405, 2024.
- [29] H. Landström, "The metamorphosis of modern entrepreneurship education: Transitioning to digital advisory models," *Academy of Management Learning & Education*, vol. 23, no. 3, pp. 412–431, 2024.
- [30] S. Alter, "Making sense of AI systems, agents, and capabilities in enterprise architectures: Bridging the execution gap," *MIS Quarterly Executive*, vol. 23, no. 2, pp. 115–134, 2024.
- [31] Y. Zhou, X. Sardi, and M. Habib, "Amplifier or substitute? A systematic review of generative AI's impact on higher-order cognitive skills among university students," *Frontiers in Psychology*, vol. 17, Art. no. 186393, 2026.
- [32] A. Agrawal, J. Gans, and A. Goldfarb, "How Generative AI alters the economics of enterprise scaling," *Harvard Business Review*, vol. 102, no. 6, pp. 84–93, 2024.
- [33] J. D. Farmer and J. Geanakoplos, "The application of Shannon entropy to economic systems: Measuring systemic disorganization," *Physica A: Statistical Mechanics and its Applications*, vol. 622, Art. no. 128841, 2023.
- [34] S. I. Wu and L. C. Lin, "Applications of economic cybernetics and information entropy in firm-level operational diagnostics," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 54, no. 1, pp. 512–524, 2024.
- [35] J. Zheng and W. Zhang, "Financing digital edupreneurs: Capital constraints and bootstrapping mechanisms in emerging markets," *Journal of Business Venturing Insights*, vol. 21, e00412, 2024.
- [36] World Bank, *World Bank Enterprise Surveys: Analytical Framework and Global Firm-Level Data Assessment*, Washington, D.C.: World Bank Group, 2025.
- [37] J. M. Crant and K. M. Roloff, "Creator burnout and algorithmic pressure in the influencer ecosystem," *Journal of Applied Psychology*, vol. 109, no. 8, pp. 1121–1138, 2024.
- [38] GoDaddy Venture Forward, *Microbusiness Density and Local Economic Resilience: A Multi-Year Transactional Assessment*, Whitepaper Report, 2024.
- [39] Y. Su, "Task-Gated Attentive Multi-Task Ensemble Learning for Joint Energy and Latency Prediction in Cloud Telemetry," *TechRxiv*, Tech. Rep. 177220004, 2024.
- [40] D. Harrison and S. Rouse, "Construct validity of an objective categorical measure of diversification strategy using entropy formulations," *Strategic Management Journal*, vol. 45, no. 8, pp. 1541–1563, 2024.
- [41] D. Harrison and S. Rouse, "Construct validity of an objective categorical measure of diversification strategy using entropy formulations," *Strategic Management Journal*, vol. 45, no. 8, pp. 1541–1563, 2024.

- [42] M. Asadi, A. Di Crescenzo, and S. Spina, "On the dynamic cumulative residual entropy: Properties and applications in business networks," *Applied Stochastic Models in Business and Industry*, vol. 40, no. 2, pp. 234–257, 2024.
- [43] J. Li and M. Wang, "Digital twin-based risk assessment and decision support systems for university student entrepreneurial projects," *Humanities and Social Sciences Communications*, vol. 12, no. 1, Art. no. 204, 2025.
- [44] S. Park and J. Yan, "Explainable AI in manufacturing and industrial cyber-physical systems: A survey of SHAP and LIME methodologies," *IEEE Access*, vol. 12, pp. 13497–13515, 2024.
- [45] L. M. Martinez, "The ship-then-shop model: A cybernetic approach to sustainable transition in digital commerce supply chains," *Kybernetes*, vol. 53, no. 4, pp. 1237–1258, 2024..
- [46] A. Huggins and S. Roy, "Effective sample size approximations as generalized entropy measures in machine learning decision structures," *arXiv*, arXiv:2402.11582, Feb. 2024.
- [47] C. Tsallis and H. J. Jensen, "Non-extensive statistical mechanics and intermittent dynamics in financial signals," *Physica A: Statistical Mechanics and its Applications*, vol. 632, Art. no. 119820, 2024.
- [48] M. Urban and F. Kanguwe, "Organisational configurations explaining the entrepreneurial orientation–performance relationship: A focus on bricolage capability," *Journal of Innovation and Entrepreneurship*, vol. 13, no. 1, pp. 1–29, 2024.
- [49] T. Takahashi, "Predictive telemetry and SHAP interpretations: Re-engineering algorithmic interventions in incubator analytics," *Expert Systems with Applications*, vol. 241, Art. no. 122610, 2024.
- [50] K. M. Roloff and S. Alter, "Human-AI collaboration in solopreneur networks: Bridging cognitive constraints through shared agency," *MIS Quarterly*, vol. 48, no. 4, pp. 1445–1468, 2024.

ARTIFICIAL INTELLIGENCE FOR EDUCATION

How Digital Storytelling Shapes Children's Thinking: A Scoping Review of Cognitive Processes and Developmental Outcomes

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ABSTRACT — *The rapid evolution of artificial intelligence (AI) and digital technologies has transformed storytelling practices in early childhood education. AI-supported digital storytelling has emerged as a promising pedagogical approach capable of enhancing children's cognitive development, narrative thinking, language acquisition, creativity, and socioemotional interaction between the children ages 1–6 years. This scoping review synthesizes contemporary evidence regarding how digital storytelling shapes children's thinking processes and developmental outcomes. PRISMA-ScR is an extension of the original PRISMA guideline for systematic reviews and meta-analyses, newer methodological papers stress aligning scoping reviews and JBI guidance with PRISMA-ScR for consistency and rigor [1]. Fifteen core articles from 2023–2025 were identified and analyzed together with additional supporting literature.*

Findings indicate positive effects on critical thinking, self-regulated learning, narrative competence, language development, emotional engagement, creative thinking, early scientific reasoning, cognitive flexibility, expressive communication, and collaborative learning. Emerging themes include AI literacy, culturally responsive storytelling, adaptive learning systems, and dialogic interaction. Nevertheless, gaps remain in longitudinal evidence, ethical considerations, teacher preparedness, developmental appropriateness, and authentic preschool implementation. This review contributes by proposing an integrated conceptual framework linking AI-supported digital storytelling, cognitive processes, and developmental outcomes in early childhood education.

KEYWORDS: *Digital storytelling, artificial intelligence, early childhood education, cognitive development, narrative thinking, preschool children, AI-supported storytelling, developmental outcomes.*

I. INTRODUCTION

The integration of artificial intelligence (AI) into early childhood education has transformed pedagogical practices, with AI-supported digital storytelling emerging as an innovative approach that combines multimodal technologies, adaptive learning, narrative interaction, and generative AI to support children's cognitive and developmental growth. Digital storytelling enhances language acquisition, creativity, narrative competence, problem-solving, and emotional engagement while serving as a cognitive scaffold that helps preschool children organize

experiences, construct meaning, and develop higher-order thinking skills [2]; [3]. Contemporary early childhood education emphasizes learner-centered and inquiry-based approaches aligned with children's developmental needs [4].

Traditional storytelling has evolved into interactive digital experiences through AI-generated visuals, conversational agents, adaptive narratives, and multimedia environments, enabling active participation and collaborative meaning-making [5]. Studies further indicates that digital storytelling can foster critical cognitive domains such as memory retention, divergent thinking, self-regulation, and scientific reasoning among young learners [6]; [7].

The emergence of generative AI has further advanced personalized storytelling by adapting narratives to children's developmental levels, interests, and cultural backgrounds through responsive dialogue systems and multimodal interaction, thereby increasing engagement, motivation, and cognitive participation [8], [9]. Despite increasing research, evidence remains fragmented across educational technology, developmental psychology, language education, and early childhood pedagogy.

Most studies examine isolated outcomes such as literacy, engagement, or technology implementation, with limited synthesis of cognitive processes and developmental outcomes. Furthermore, scoping evidence specifically addressing how AI-supported storytelling influences the thinking processes of children aged 1–6 years remains limited. This scoping review therefore aims to synthesize current evidence on the relationship between AI-supported digital storytelling, cognitive processes, and developmental outcomes in early childhood education. Specifically, the review addresses the following research questions:

1. How does AI-supported digital storytelling influence children's cognitive processes?
2. What developmental outcomes are associated with digital storytelling among children aged 1–6 years?
3. How has AI-supported storytelling developed, and what are its associated developmental outcomes?

II. METHODOLOGY

This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) to systematically map evidence on AI-supported digital storytelling and its influence on children's cognitive processes and developmental outcomes. PRISMA-ScR is appropriate for synthesizing emerging educational technologies and identifying research gaps within rapidly evolving interdisciplinary fields [10], [1].

A. Research Design

This study employed a scoping review methodology guided by the PRISMA Extension for Scoping Reviews (PRISMA-ScR). Scoping reviews are appropriate for mapping emerging research areas, identifying conceptual boundaries, synthesizing evidence, and highlighting research gaps within rapidly developing interdisciplinary fields [1].

B. Eligibility Criteria

The review included English-language peer-reviewed empirical, conceptual, review, and mixed-method studies published between 2023 and 2025 that examined digital storytelling, AI-supported storytelling, or interactive storytelling involving children aged 1–6 years. Studies focusing on adolescents, adults, non-educational contexts, non-English publications, and duplicates were excluded.

C. Information Sources

The review synthesized 15 core studies identified through matrix mapping, complemented by supporting literature from Scopus-indexed journals, conference proceedings, and educational technology publications. The selected studies examined the effects of AI-supported and digital storytelling on cognitive development, language and literacy, narrative competence, creativity, self-regulated learning, scientific reasoning, emotional engagement, collaboration, and culturally responsive learning in early childhood education.

D. Data Extraction and Analysis

Data were extracted on study focus, educational context, methodology, cognitive processes, developmental outcomes, AI integration, key findings, and research gaps. A thematic synthesis was then conducted to identify recurring patterns, emerging themes, and conceptual relationships regarding the influence of AI-supported storytelling on children's cognitive and developmental outcomes in early childhood education.

III. PRISMA FLOW DIAGRAM

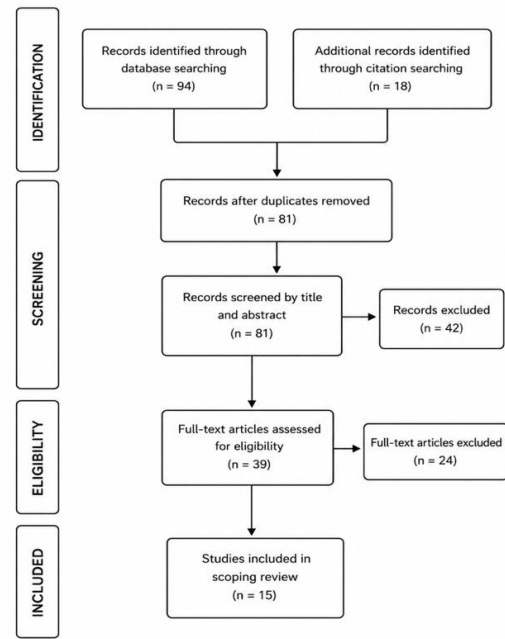


Figure 1. Prisma Flow Diagram.

Based on the figure 1 shown above, the final selection of studies included in this scoping review consisted of 15 articles published between 2023 and 2025 that examined digital storytelling, AI-supported storytelling, interactive storytelling, and technology-enhanced narrative learning within early childhood education contexts. The selected literature included empirical studies, systematic reviews, meta-analyses, conceptual papers, qualitative, phenomenological, quasi-experimental, randomized controlled, and design-based research, providing comprehensive evidence on cognitive development, literacy, creativity, emotional engagement, and self-regulated learning.

Most studies were empirical, evaluating the effects of digital storytelling interventions on children's cognitive and developmental outcomes. For example, [6] employed a one-group pretest-posttest design to examine cognitive development, [3] conducted a randomized controlled trial on AI-powered dialogic storytelling for science learning, and [11], used a phenomenological approach to investigate expressive language development. Broader evidence was synthesized through systematic reviews and meta-analyses in [12], [13] and [14].

The reviewed studies were published in peer-reviewed journals, conference proceedings, and educational publications, including several Scopus-indexed journals such as [13], [3], [9], and [2]. Additional publications appeared in reputable outlets including *Frontiers in Psychology*, *SAGE Open*, *Journal of Pedagogical Research*, *Revista Eletrônica de Educação*, and conference proceedings such as ICECEM and ICISTECH, enabling the review to capture both established and emerging evidence.

The literature also represented Scopus Q1, Q2, and Q3 journals alongside peer-reviewed conference proceedings, strengthening the scholarly quality and reliability of the review. Collectively, these publications demonstrate the growing global interest in AI-supported digital storytelling across educational technology, cognitive development, literacy learning, and interactive media research.

IV. CHARACTERISTIC OF INCLUDED STUDIES

The final sample comprised 15 studies from 2023 to 2025 examining digital storytelling, AI-supported storytelling, interactive storytelling, and technology-enhanced narrative learning in early childhood education.

Table 2 Characteristic of Reviewed Studies

Author (s)	Focus	Methodology	Major Contribution
Muamaroh & Destiana	DST and cognitive development	Quantitative	Improved critical thinking and problem-solving
Urgessa <i>et al.</i>	DST and self-regulated learning	Conceptual Review	Cognitive and emotional regulation
Prastyo <i>et al.</i>	DST and expressive language	Quantitative	Richer vocabulary and participation
Chen & Huang	Picture books and cognition	Conceptual analysis	Memory and critical thinking
Xing <i>et al.</i>	Interactive reading	Meta-analysis	Improved narrative ability
Wan Mohd Nasir <i>et al.</i>	Creative thinking via DST	Quasi-experimental	Enhanced divergent thinking
Chen	AI storytelling and literacy	Systematic review	Improved vocabulary and cognition
Zini	Narrative competence	Design-based research	Narrative coherence framework
Xu <i>et al.</i>	AI interactive science storytelling	Experimental	Increased science learning
Sun <i>et al.</i>	Parent perspectives on AI storytelling	Qualitative	Child-centered AI features

Baskara	Culturally grounded storytelling	Literature review	Creativity and cultural cognition
Mustafa <i>et al.</i>	DST and literacy		Reading and comprehension improvement
Liu <i>et al.</i>	Digital technologies and literacy	Systematic review	Narrative and vocabulary development
Xiao <i>et al.</i>	Emotional engagement	Qualitative	Aesthetic literacy development
Han & Cai	AI storytelling systems	Qualitative	Safe and adaptive storytelling design

The selected studies represented diverse methodological approaches, including quantitative, qualitative, experimental, quasi-experimental, systematic review, meta-analysis, conceptual analysis, design-based research, and literature review. This methodological diversity enabled a comprehensive examination of the cognitive, linguistic, emotional, and developmental impacts of AI-supported storytelling in early childhood education.

Most studies adopted empirical designs to evaluate the effectiveness of digital storytelling interventions. For example, [6] reported improvements in preschool children's critical thinking and problem-solving, [7] demonstrated enhanced divergent thinking through a quasi-experimental study, and [3] found that AI-supported interactive storytelling significantly improved science learning and engagement.

Conceptual and review-based studies expanded the theoretical understanding of storytelling technologies. [15] highlighted the role of digital storytelling in supporting self-regulated learning, [16] emphasized memory and critical thinking through multimodal picture books, and [17] discussed the potential of generative AI for culturally responsive storytelling and creativity.

Systematic reviews and meta-analyses further strengthened the evidence base. [13] and [14] reported consistent improvements in language, literacy, vocabulary, and cognitive development through AI-supported storytelling and digital technologies, while [12] demonstrated significant gains in children's narrative abilities through interactive reading.

The studies were published in Scopus-indexed journals, peer-reviewed educational journals, and conference proceedings, reflecting the increasing international interest in AI-supported storytelling within educational technology, literacy development, cognitive development, and early childhood education. Collectively, the evidence provides a balanced understanding of current research trends and supports the educational value of AI-supported digital storytelling.

V. FINDINGS AND DISCUSSION

The reviewed studies consistently demonstrate that AI-supported digital storytelling positively influences children's cognitive, linguistic, and developmental outcomes. Thematic synthesis identified three major themes: (A) digital storytelling and cognitive processes, (B) narrative thinking and language development, and (C) AI-supported storytelling and developmental outcomes.

A. Digital Storytelling and Cognitive Processes

The literature consistently shows that AI-supported digital storytelling enhances critical thinking, problem-solving, narrative reasoning, memory, metacognition, and self-regulation. [6] reported significant improvements in preschool children's critical thinking, problem-solving, and cause-and-effect reasoning, while [15] highlighted its role in supporting cognitive regulation and self-regulated learning.

Interactive storytelling further promoted divergent thinking and creative reasoning [7], consistent with evidence that multimodal storytelling enhances imagination and cognitive flexibility [17], [4]. AI-powered storytelling also increased science comprehension, verbal engagement, vocabulary acquisition, and cognitive participation through adaptive interaction [3], [13]. Overall, digital storytelling functions as a cognitive scaffold that strengthens memory, symbolic understanding, and conceptual organization [16].

B. Narrative Thinking and Language Development

Narrative thinking emerged as a key developmental outcome, supporting children's ability to organize ideas, sequence events, and communicate meaning. Digital storytelling significantly improved expressive language, vocabulary, and speaking confidence [11], while interactive storytelling enhanced narrative competence and comprehension [12]. AI-supported storytelling further promoted collaborative story creation through physical-digital interaction [5].

Emotional engagement also played an important role, with teacher-child interaction, body language, and multimodal communication enriching literacy experiences and sustaining attention during storytelling [18]. Interactive visual narratives additionally supported symbolic representation, emotional intelligence, and problem-solving [17].

C. To Evaluate the Development of AI-Supported Storytelling and Development Outcomes

AI-supported storytelling enables adaptive, personalized, and culturally responsive learning experiences. Safe, co-creative, and age-appropriate AI systems are essential for young children [19], while parents value adaptive and child-centered interaction [8]. Culturally grounded storytelling further promotes creativity and cultural identity [17], and generative AI can personalize narrative complexity and learning pathways according to children's developmental needs [7].

Across the reviewed studies, AI-supported storytelling contributed to cognitive development, language acquisition, creativity, social interaction, emotional engagement, AI literacy, and scientific reasoning. Nevertheless, challenges

related to AI bias, screen exposure, developmental appropriateness, privacy, and teacher preparedness remain significant, highlighting the need for stronger pedagogical frameworks and ethical implementation guidelines [2], [19].

VI. CONCEPTUAL FRAMEWORK

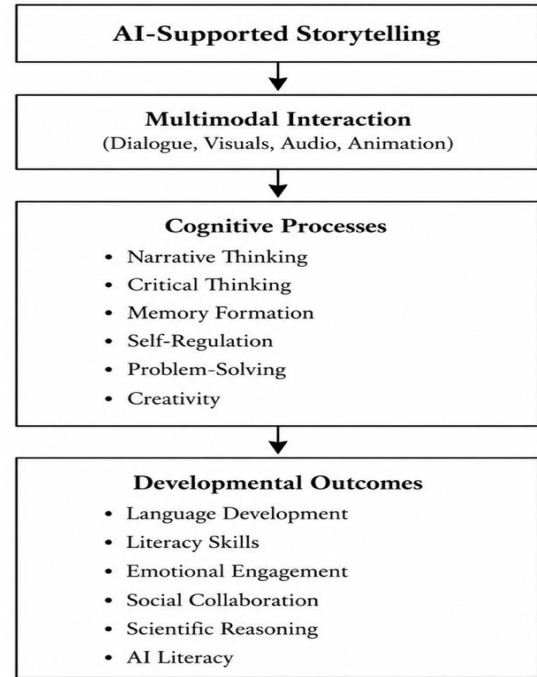


Figure 2. Conceptual Framework.

The conceptual framework illustrates the relationship between AI-supported storytelling, multimodal interaction, cognitive processes, and developmental **outcomes** in early childhood education. AI-supported storytelling serves as the instructional foundation, integrating generative AI, adaptive narrative systems, and interactive dialogue to provide personalized learning experiences that enhance children's engagement and motivation [5], [17].

Multimodal interaction—including dialogue, visuals, audio, and animation—acts as the central mechanism linking AI-supported storytelling to cognitive development. Such environments improve attention, comprehension, knowledge retention, and active participation while supporting constructivist and sociocultural learning through interactive experiences [20], [3].

The framework proposes that multimodal storytelling enhances key cognitive processes, including narrative thinking, critical thinking, memory formation, self-regulation, problem-solving, and creativity. These processes are fostered through narrative sequencing, inquiry-based interaction, repeated multimodal exposure, and collaborative storytelling, contributing to higher-order thinking and cognitive flexibility [12], [21].

Enhanced cognitive processes subsequently lead to positive developmental outcomes, including language and literacy development, emotional engagement, social collaboration, scientific reasoning, and emerging AI

literacy [14], [2], [22]. Overall, the framework demonstrates that AI-supported storytelling is a comprehensive pedagogical approach that promotes personalized, meaningful, and cognitively stimulating learning experiences for young children through multimodal interaction [23].

VII. RESEARCH GAP

Despite the growing evidence supporting AI-supported storytelling in early childhood education, several important research gaps remain. First, most studies rely on short-term interventions, with limited longitudinal evidence on sustained cognitive, literacy, creativity, self-regulation, and developmental outcomes [12], [13], [23]. Second, empirical research involving children aged **1–3 years** remains scarce, despite this period being critical for language, cognitive, and socio-emotional development [5]. Third, existing studies are concentrated in technologically advanced countries, highlighting the need for culturally responsive and multilingual AI-supported storytelling in underrepresented educational contexts [2], [3], [17].

Fourth, teacher readiness, AI literacy, and professional development receive limited attention, despite their importance for effective classroom implementation [22], [23]. Fifth, ethical issues including privacy, algorithmic bias, screen exposure, emotional dependency, and developmental appropriateness require stronger investigation and clearer implementation guidelines [5], [22]. Finally, the lack of standardized frameworks for assessing cognitive, linguistic, emotional, and social outcomes limits cross-study comparison and evidence synthesis, emphasizing the need for consistent evaluation approaches [14].

VIII. IMPLICATIONS FOR EARLY CHILDHOOD EDUCATION

The findings suggest that AI-supported digital storytelling has significant potential to enhance early childhood education by creating interactive, adaptive, and child-centered learning environments that improve engagement, motivation, and knowledge construction through multimodal learning [20], [24]. AI-supported storytelling also promotes inquiry-based learning, enabling children to explore, solve problems, and develop higher-order thinking through adaptive narratives and interactive dialogue [5], [22].

The reviewed studies further indicate that AI-supported storytelling strengthens multimodal literacy, cognitive flexibility, creativity, collaborative communication, and scientific reasoning by integrating text, visuals, audio, animation, and personalized learning pathways [3], [25], [26]. In addition, culturally responsive AI-generated stories can foster inclusivity and reflect children's linguistic and cultural backgrounds, although careful design is required to minimize cultural bias and ensure equitable representation [22], [27].

Successful implementation requires teacher AI literacy, professional development, ethical governance, and child-centered AI frameworks to address privacy, algorithmic bias, developmental appropriateness, and equitable access [5], [28], [29]. Finally, curriculum designers should integrate adaptive AI storytelling systems that personalize narrative complexity and learning experiences to support diverse developmental needs and inclusive early childhood education [24].

IX. CONCLUSION

This scoping review demonstrates that AI-supported digital storytelling positively influences children's cognitive and developmental outcomes in early childhood education. Across the reviewed studies, AI-supported storytelling enhanced critical thinking, narrative competence, language development, creativity, self-regulated learning, emotional engagement, scientific reasoning, and multimodal literacy by integrating adaptive narratives, interactive technologies, and multimodal communication [5], [20], [23], [25]. These findings highlight AI-supported storytelling as an effective child-centered pedagogical approach that promotes active participation, personalized learning, and higher-order cognitive development [24].

Despite these benefits, important challenges remain, including the lack of longitudinal evidence, limited research involving children aged **1–3 years**, insufficient teacher AI literacy, and concerns regarding privacy, algorithmic bias, developmental appropriateness, and ethical implementation [29]. The review also emphasizes the need for culturally responsive AI storytelling that reflects diverse linguistic and cultural contexts [28].

Overall, AI-supported storytelling represents a promising educational innovation with the potential to transform early childhood learning. Future research should prioritize longitudinal classroom studies, culturally adaptive AI frameworks, teacher professional development, and ethical implementation to ensure safe, inclusive, and sustainable integration of AI in early childhood education.

REFERENCES

- [1] Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., & Lewin, S. (2018). PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals of Internal Medicine*, 169(7), 467–473. <https://doi.org/10.7326/M18-0850>
- [2] Han, A., & Cai, Z. (2023). *Design implications of generative AI systems for visual storytelling for young learners*. ResearchGate; unknown. https://www.researchgate.net/publication/371693449_Design_implications_of_generative_AI_systems_for_visual_storytelling_for_young_learners
- [3] Xu, Y., He, K., Levine, J., Ritchie, D., Pan, Z., Bustamante, A., & Warschauer, M. (2024). *Artificial Intelligence Enhances Children's Science Learning From Television Shows*. *Osf.io*. https://osf.io/preprints/edrxiv/5kypd_v1
- [4] Rehman, N., & Harrison, R. (2025). *Generative AI and Pedagogics Design: Revolutionizing Early Childhood Education and Teaching "Why."* *ResearchGate*. <https://doi.org/10.13140/RG.2.2.21948.14728>

- [5] Choi, N., Peace Cyebukayire, & Choi, J. D. (2025, April 17). *Tinker Tales: Interactive Storytelling Framework for Early Childhood Narrative Development and AI Literacy*. <https://doi.org/10.48550/arXiv.2504.13969>
- [6] Muamaroh, F., & Destiana, E. (2025). *The Influence of Digital Storytelling on the Cognitive Development of 5-6 Year Old Children at RA Darul Arqom*. <https://doi.org/10.21070/ups.9184>
- [7] Wan Mohd Nasir, W. M. F., Halim, L., & Arsad, N. M. (2024). Fostering creative thinking skills through digital storytelling. *Journal of Pedagogical Research*, 8(3). <https://doi.org/10.33902/jpr.202427318>
- [8] Prilop, C. N., Mah, D.-K., Jacobsen, L. J., Hansen, R. R., Weber, K. E., & Hoya, F. (2025). Generative AI in teacher education: Educators' perceptions of transformative potentials and the triadic nature of AI literacy explored through AI-enhanced methods. *Computers and Education: Artificial Intelligence*, 9, 100471. <https://doi.org/10.1016/j.caeai.2025.100471>
- [9] Sun, Y., Chen, J., Yao, B., Liu, J., Wang, D., Ma, X., Lu, Y., Xu, Y., & He, L. (2024). Exploring Parent's Needs for Children-Centered AI to Support Preschoolers' Interactive Storytelling and Reading Activities. *Proceedings of the ACM on Human-Computer Interaction*, 8(CSCW2), 1–25. <https://doi.org/10.1145/3687035>
- [10] Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a Methodological Framework. *International Journal of Social Research Methodology*, 8(1), 19–32. <https://doi.org/10.1080/1364557032000119616>
- [11] Danang Prastyo, Budi Purwoko, Rofik Jalal Rosyanafi, Desika Putri Mardiani, & Ardhana Reswari. (2025). Digital Storytelling in Developing Expressive Language Skills in Early Childhood: A Phenomenological Study. *Al-Hikmah Indonesian Journal of Early Childhood Islamic Education*, 9(1), 62–72. <https://doi.org/10.35896/ijecie.v9i1.986>
- [12] Xing, L., Tang, Y., Liu, Q., Chen, H., & Su, J. (2025). The effects of interactive reading on young children's narrative abilities: a meta-analytic study. *Frontiers in Psychology*, 16. <https://doi.org/10.3389/fpsyg.2025.1653511>
- [13] Chen, G. (2024). The Impacts of AI-Driven Storytelling Applications on Language Acquisition and Literacy Development in Early Childhood Education: A Systematic Review. *Asian Journal of Advanced Research and Reports*, 18(11), 1–12. <https://doi.org/10.9734/ajarr/2024/v18i11770>
- [14] Liu, S., Reynolds, B. L., Thomas, N., & Soyoo, A. (2024). The Use of Digital Technologies to Develop Young Children's Language and Literacy Skills: a Systematic Review. *SAGE Open*, 14(1). <https://doi.org/10.1177/21582440241230850>
- [15] Dinaol Urgessa Gita, Bekalu Ferede, & Tondeur, J. (2025). Exploring the Association between Digital Storytelling and Self-Regulated Learning: A Review of Claims. *Computers and Education Open*, 100267–100267. <https://doi.org/10.1016/j.cao.2025.100267>
- [16] Chen, M., & Huang, Y.-C. (2025). Analysis on the role of picture books in children's cognitive development education. *Edelweiss Applied Science and Technology*, 9(3), 1916–1925. <https://doi.org/10.55214/25768484.v9i3.5718>
- [17] Baskara, R. (2024). Fostering Culturally Grounded Learning: Generative AI, Digital Storytelling, And Early Childhood Education. Uinsaizu.ac.id. <https://proceedings.uinsaizu.ac.id/index.php/icecem/article/view/463/391>
- [18] Xiao, M., Rong, W., & Fadzilah Amzah. (2023). *Experience of Beauty: Valuing Emotional Engagement and Collaboration in Teacher-Child Storytelling Activities*. 22(2), 165–187. https://www.researchgate.net/publication/368959751_Experience_of_Beauty_Valuing_Emotional_Engagement_and_Collaboration_in_Teacher-Child_Storytelling_Activities
- [19] Iro Voulgari, Konstantinos Lavidas, Spyridon Aravatinos, Soultana Sypsa, & Sfyroera, M. (2024, July 2). *Exploring the Role, Implementation, and Educational Implications of AI in Early Childhood Education*. https://doi.org/10.1007/978-3-031-64312-5_4
- [20] Mayer, R. E. (2024). The Past, Present, and Future of the Cognitive Theory of Multimedia Learning. *Educational Psychology Review*, 36(8), 1–25. <https://doi.org/10.1007/s10648-023-09842-1>
- [21] Adeyemi, V. (2025). *The Impact of Digital Technology on Child's Cognitive and Social Development: Implications for Education - Premier Science*. Premier Science. <https://premierscience.com/pjp-25-808/>
- [22] Berson, I. R., Berson, M. J., & Luo, W. (2025). Innovating responsibly: ethical considerations for AI in early childhood education. *Innovating Responsibly: Ethical Considerations for AI in Early Childhood Education*, 1(1). <https://doi.org/10.1007/s44436-02500003-5>
- [23] Zhang, K. & Aslan, A. B. (2021). AI technologies for education: Recent research & future directions. *Computers and Education: Artificial Intelligence*, 2(100025), 100025. <https://doi.org/10.1016/j.caeai.2021.100025>
- [24] Larson, S., Olson, C., & Habeeb Agoro. (2025, August 1). *AI-Powered Personalized Learning in Early Childhood: Evidence of Benefits and Risks for Development*. https://www.researchgate.net/publication/394841982_AI-Powered_Personalized_Learning_in_Early_Childhood_Evidence_of_Benefits_and_Risks_for_Development
- [25] Fei Victor Lim, & Tan-Chia, L. (2022). Multimodal Literacy Learning with Digital Texts. *Routledge EBooks*, 54–70. <https://doi.org/10.4324/9781003258513-4>
- [26] Sakır, A. (2026). The Use of Digital Storytelling in Early Childhood Education: A Systematic Review. *MIER Journal of Educational Studies Trends and Practices*, 18–46. <https://doi.org/10.52634/mier/2026/v16/i1/2899>
- [27] Li, X., & Yu, S. (2025). Journal of Early Childhood Teacher Education Culturally responsive AI module in early childhood teacher education: an action research. *Journal of Early Childhood Teacher Education*, 1–17. <https://doi.org/10.1080/10901027.2025.2552973>
- [28] Ayanwale, M. A., Sanusi, I. T., Adelana, O. P., Aruleba, K. D., & Oyelere, S. S. (2022). Teachers' readiness and intention to teach artificial intelligence in schools. *Computers and Education: Artificial Intelligence*, 3(100099), 100099. <https://doi.org/10.1016/j.caeai.2022.100099>
- [29] UNICEF. (2021). *Policy Guidance on AI for Children 2.0* <https://www.unicef.org/innocenti/media/1341/file/UNICEF-Global-Insight-policy-guidance-AI-children-2.0-2021.pdf>

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Beyond Digital Skills: Investigating AI Readiness among TVET Students in the Era of Industry 5.0

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ABSTRACT — As Artificial Intelligence (AI), intelligent automation, and Industry 5.0 technologies continue to evolve, the demand for a workforce capable of adapting to AI-driven industrial environments has increased substantially. Technical and Vocational Education and Training (TVET) institutions are expected to equip students with the competencies required for this transformation. However, previous studies have examined AI literacy, digital competency, and technological readiness independently, with limited attention to their combined influence on AI readiness and the psychological mechanism underlying these relationships among TVET students. Therefore, this study investigates the influence of AI literacy, digital competency, adaptive learning skills, and Industry 5.0 awareness on AI readiness, with technological self-efficacy serving as a mediator. A quantitative cross-sectional design involving 384 TVET students in Malaysia was employed. Data were analysed using SPSS and Structural Equation Modeling (SEM) with AMOS. The findings revealed that AI literacy ($\beta = 0.18, p < 0.05$), digital competency ($\beta = 0.29, p < 0.001$), adaptive learning skills ($\beta = 0.25, p < 0.01$), Industry 5.0 awareness ($\beta = 0.26, p < 0.001$), and technological self-efficacy ($\beta = 0.36, p < 0.001$) significantly and positively influenced AI readiness. Bootstrapping analysis further indicated that technological self-efficacy partially mediated the relationships between the four competency dimensions and AI readiness. The findings provide practical implications for policymakers, educators, and TVET institutions in strengthening AI-oriented vocational education and developing a future-ready workforce.

KEYWORDS: Artificial Intelligence Readiness; Industry 5.0; TVET Students; Technological Self-Efficacy; Digital Competency; Adaptive Learning Skills.

I. INTRODUCTION

Artificial Intelligence (AI), intelligent automation, robotics, cyber-physical systems, and data-driven technologies have been the driving force behind the era of Industry 5.0 (I5.0) which has been characterized by rapid advances over the past few years across the globe [1,2]. While Industry 4.0 mainly emphasized automation, productivity and interlinked manufacturing systems, Industry 5.0 brings about a more human-centered industrial revolution that combines technological intelligence with the creativity, sustainability, resilience and collaborative decision-making of humans [3]. AI technologies are not just tools for the workplace, but

partners in innovation, intelligent problem-solving, and strategic industrial processes, as part of this emerging industrial ecosystem. This has led to a growing demand for employees with the ability to communicate with intelligent technologies, as well as the capacity to be flexible and confident with technology and possess future-oriented skills [4].

In this shift, TVET institutions are particularly important in training future skilled workers in an industrial environment that is driven by artificial intelligence. With the technological changes in the world, socio-economic sectors are looking for an increasing number of vocational graduates who are capable of interacting with AI-based systems, understanding digital information, learning new technologies, and continuously enhancing their skills to meet technological disruptions [5]. But there are still many TVET institutions that focus on operational skills instead of smart technological adaptability, AI collaboration and future-oriented industrial skills. This is causing an increasing gap between the knowledge and skills that industry expects and the skills that graduates have, especially in the context of intelligent robots, predictive analytics, autonomous systems and industries that integrate artificial intelligence (AI) into production lines [6]. AI literacy is among the most crucial skills needed in Industry 5.0. AI literacy is defined as the capacity to comprehend, assess, engage with, and engage with AI technologies in education and industry in a responsible manner. Students are expected to have basic knowledge of AI systems and their applications in various fields, including manufacturing, logistics, engineering, healthcare, and technical services, as AI increasingly becomes a part of these industries [7].

Digital competency is another key factor in workforce readiness for Industry 5.0, alongside AI literacy. Digital competency is the knowledge, technical skills, and attitudes needed to work effectively with digital technologies in communication, collaboration, innovation, and problem-solving. Students are often introduced to digital devices and online platforms, but this does not necessarily guarantee they are competent in operating complex modern industrial technologies. In the context of Industry 5.0, there is a need for advanced digital skills, such as the ability to interact with

systems intelligently, interpret industrial data, collaborate digitally, and integrate technology into operations [8].

In addition, adaptive learning skills are increasingly important in the fast-changing technological context. Industry 5.0 involves continuous technological development and dynamic industry changes, and demands workers who can learn throughout their lives, think flexibly, and develop skills quickly. Pupils who have developed strong adaptive learning skills are more likely to adapt positively to technological disruptions, learn new technologies, and adapt to intelligent industrial systems [4]. Typical vocational education, however, tends to focus on standardized competency frameworks and precise technical procedures while neglecting the development of adaptive learning behaviors.

Another important dimension influencing students' preparedness is Industry 5.0 awareness. Industry 5.0 awareness refers to students' understanding of intelligent industrial ecosystems that integrate AI, sustainability, resilience, and human-machine collaboration. Students with stronger awareness of Industry 5.0 are more likely to recognize the importance of future-oriented technological competencies and AI-related skill development [2]. Nevertheless, awareness of Industry 5.0 concepts among TVET students remains relatively underdeveloped, as educational discussions frequently focus on automation and digitization without adequately emphasizing the human-centered dimensions of Industry 5.0.

Technological self-efficacy is one of the psychological factors that has become significant in relation to AI readiness in response to these challenges. Technological self-efficacy is the self-confidence that a person has in "using, managing and adapting to technological systems" effectively. For Social Cognitive Theory (SCT), a person who has high self-efficacy has greater self-confidence in the use of challenging technology, is more persistent in learning, and is more adaptable to technological changes [9]. In the context of Industry 5.0, technological self-efficacy could serve as a key mediation process between students' skills and knowledge and their readiness for AI. Although there has been a growing amount of research interest in the integration of AI and the technical readiness, there are still several important gaps in research to be addressed. Research on TVETs is mostly conducted among university students and in higher education institutions, with few studies conducted with TVET students. Furthermore, the previous studies have mostly analyzed AI literacy, digital competency, or technological readiness individually, without considering multiple dimensions of competency together in one framework of AI readiness for Industry 5.0 [5]. As such, little is known about the impact of the combination of AI literacy, digital competency, adaptive learning skills and Industry 5.0 awareness on the overall AI readiness of TVET students.

Accordingly, this study proposes a comprehensive framework to examine the influence of AI literacy, digital competency, adaptive learning skills, and Industry 5.0 awareness on AI readiness among TVET students, with technological self-efficacy as a mediating mechanism. There are three major contributions stemming from the study's novelty. First, the study brings together various Industry 5.0 competencies into a common framework for AI readiness. Secondly, the study defines technological self-efficacy as a psychological mediator between competencies and AI readiness. Third, this study empirically concentrates on the

TVET students as the future technical workforce directly involved in the Intelligent industrial ecosystem. Therefore, the study addresses the following research questions:

RQ1: How does AI literacy influence technological self-efficacy among TVET students for Industry 5.0?

RQ2: How does digital competency influence technological self-efficacy among TVET students for Industry 5.0?

RQ3: How do adaptive learning skills influence technological self-efficacy among TVET students for Industry 5.0?

RQ4: How does Industry 5.0 awareness influence technological self-efficacy among TVET students for Industry 5.0? and

RQ5: How does technological self-efficacy influence AI readiness among TVET students for Industry 5.0?

The results are likely to offer valuable theoretical and practical guidance for teachers, policy-makers, and TVET institutions in enhancing AI-based vocational education and the future readiness of the workforce in an intelligent, sustainable, and human-centered industrial environment.

II. LITERATURE REVIEW

A. Theoretical Perspective

The Unified Theory of Acceptance and Use of Technology (UTAUT) and Social Cognitive Theory (SCT) are used to explain the factors influencing TVET students' Industry 5.0 readiness for Artificial Intelligence (AI). Together, these theories provide a holistic framework for understanding AI readiness by encompassing students' exposure to AI, technological perceptions, confidence, behavioural competencies, and willingness to engage with emerging technologies [10,11]. Understanding both technological acceptance and psychological readiness is essential for explaining how TVET students prepare for AI-driven industrial environments.

UTAUT provides an appropriate framework for assessing readiness to adopt new technologies through its constructs of effort expectancy, performance expectancy, social influence, and facilitating conditions [12]. In Industry 5.0, AI technologies are increasingly integrated into intelligent automation, smart manufacturing, predictive maintenance, and human-machine collaboration [13]. Consequently, students' readiness to adopt AI is closely associated with their perceptions of the usefulness, accessibility, and applicability of AI-related competencies in future workplaces. AI literacy, digital competency, adaptive learning skills, and Industry 5.0 awareness therefore align with UTAUT as technological capabilities that shape students' readiness.

However, technology acceptance alone is insufficient to explain students' psychological confidence in using AI technologies. Therefore, Social Cognitive Theory (SCT) is adopted to examine the behavioural and psychological aspects of AI readiness. SCT emphasises the interaction of personal, environmental, and behavioural factors, with self-efficacy serving as one of its central constructs [14]. In this study, technological self-efficacy refers to students' confidence in operating, adapting to, and effectively utilising technological systems. It is proposed as the mediating mechanism through which AI literacy, digital competency, adaptive learning skills, and Industry 5.0 awareness influence

AI readiness. Although students may possess these competencies, they may not be fully prepared for AI-driven industrial environments without the confidence to apply them effectively in real-world contexts [15].

The integration of UTAUT and SCT enhances the study's originality by combining technological acceptance with psychological readiness to provide a comprehensive explanation of AI readiness for Industry 5.0. It also extends both theories to the TVET education context, where empirical evidence remains limited, while positioning technological self-efficacy as the key mediator linking Industry 5.0 competencies with AI readiness. This integrated framework offers deeper theoretical insight into future workforce preparedness in intelligent industrial ecosystems.

B. Proposed Conceptual Framework

The shift towards Industry 5.0 has further driven the need for students of Technical and Vocational Education and Training (TVET) to be ready for Artificial Intelligence (AI). Industry 5.0 focuses on intelligent automation, human-machine interaction, sustainability, and human-centric innovation, which will demand that future generations have technological skills and mental agility to thrive in the context of AI-driven industrial work [1,16]. Based on the literature, there are a few key factors that have been identified as playing a crucial role in shaping AI readiness, such as AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, and technological self-efficacy [9,17]. The current study draws upon the UTAUT model and SCT to investigate the roles that these competencies play in the AI readiness of TVET students. Figure 1 shows the proposed conceptual framework.

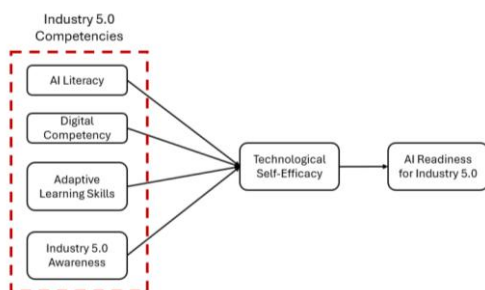


Figure 1. Proposed Conceptual Framework.

C. Hypothesis Development

The ability to use AI is rapidly becoming a core skill for future employability. AI literacy is defined as students' understanding, assessment, engagement, and responsible use of AI technologies in educational and industrial contexts. Previous research shows that AI literacy positively affects students' AI knowledge, awareness of AI applications, and their ability to adapt to a technologically advanced environment [18]. Students' readiness towards AI-driven industries is higher when they perceive AI technologies as useful and beneficial for future employability. Students who believe that AI technologies will be useful and beneficial for future employment are better prepared for AI-driven industries. However, empirical studies of TVET students remain limited, as vocational graduates are directly connected to intelligent industrial operations [19]. Based on this, the present study suggests that AI literacy positively influences the AI readiness of TVET students. Accordingly, the following hypothesis is proposed:

H1: AI literacy positively influences AI readiness for Industry 5.0 among TVET students.

Digital competency is also a crucial requirement for being workforce-ready in Industry 5.0 contexts. Digital competency is defined as having knowledge, technical skills and attitudes that enable the efficient use of digital technologies for communication, collaboration, innovation and problem solving. The students need to have advanced digital competencies because the technology of Industry 5.0 (Industry 5.0) is increasingly involving students in cyber-physical systems, intelligent automation, and operations supported by AI [20,21]. According to previous studies, a higher level of digital competency among students is associated with their technological adaptability, confidence, and involvement with new technologies [22]. Pupils who feel digital systems are controllable and beneficial are likely to be able to interact more effectively with the intelligence of industrial systems. Hence, digital competency is expected to positively impact TVET students' AI readiness. Thus, the following hypothesis is proposed:

H2: Digital competency positively influences AI readiness for Industry 5.0 among TVET students.

The dynamic nature of Industry 5.0 technologies has made adaptive learning skills increasingly important. Adaptive learning skills enable students to continuously acquire new knowledge, respond appropriately to new technologies, and adapt their learning strategies as new industrial requirements emerge. The era of Industry 5.0 demands employees who can pursue lifelong learning, adapt to changing technologies, and continuously upgrade their skills [23]. Previous work shows that students with higher adaptive learning ability are more willing to adopt new technologies and have a positive attitude towards technological change [24]. Therefore, students will be more prepared for industries that utilize AI through the development of adaptive learning skills. Therefore, the following hypothesis is proposed:

H3: Adaptive learning skills positively influence AI readiness for Industry 5.0 among TVET students.

Students' awareness and preparedness for intelligent industrial transformation are also influenced by Industry 5.0 awareness. Industry 5.0 awareness can be understood as the awareness about the use of AI in sustainability, resilience, and human-machine collaboration in the future industrial ecosystems [16,25]. Students with a higher level of awareness of Industry 5.0 are more likely to value the importance of AI-related competencies and new technologies. Previous research indicates that awareness of industrial transformation positively impacts engagement with technology, innovation readiness, and career readiness [26]. Therefore, awareness of Industry 5.0 is likely to enhance TVET students' AI readiness. Accordingly, the following hypothesis is proposed:

H4: Industry 5.0 awareness positively influences AI readiness for Industry 5.0 among TVET students.

Besides technological skills, another important psychological factor identified as a key factor in AI readiness is technological self-efficacy. Technological self-efficacy is students' confidence in their ability to use, manage, and adapt to technological systems effectively. Social Cognitive Theory suggests that those with higher self-efficacy are more inclined to approach and use complex technologies with

confidence, persist in learning, and adapt to new technological contexts [27]. According to previous research, technological self-efficacy can significantly drive students' acceptance of and involvement with AI technologies and technologically sophisticated settings [28,29]. Thus, it is expected that technological self-efficacy will positively affect TVET students' AI readiness. Thus, the following hypothesis is proposed:

H5: Technological self-efficacy positively influences AI readiness for Industry 5.0 among TVET students.

Additionally, technological self-efficacy could serve as a crucial mediator between Industry 5.0 skills and AI readiness. Students with AI literacy, digital competency, adaptive learning skills, and Industry 5.0 awareness may not be AI-ready if they lack confidence in using these skills in the real world. There is some existing literature indicating that students with higher competencies tend to have greater technological confidence, which in turn leads to greater preparedness in AI-integrated environments [30,31]. Self-efficacy is a key psychological process that shapes human actions, capabilities, and attitudes in navigating new technological landscapes, as outlined in Social Cognitive Theory (27). Thus, technological self-efficacy is suggested as a mediator in the current model.

H6: Technological self-efficacy mediates the relationship between AI literacy and AI readiness for Industry 5.0 among TVET students.

H7: Technological self-efficacy mediates the relationship between digital competency and AI readiness for Industry 5.0 among TVET students.

H8: Technological self-efficacy mediates the relationship between adaptive learning skills and AI readiness for Industry 5.0 among TVET students.

H9: Technological self-efficacy mediates the relationship between Industry 5.0 awareness and AI readiness for Industry 5.0 among TVET students.

III. METHODOLOGY

This study adopted a quantitative cross-sectional survey design to provide empirical evidence on the factors influencing Artificial Intelligence (AI) readiness among TVET students in the Industry 5.0 era. The population comprised TVET students enrolled in institutions across Malaysia, representing the future workforce for AI-driven industrial ecosystems [32]. Malaysia has approximately 1,345 TVET institutions, with students from 64 institutions participating to ensure broader representation. Based on the Krejcie and Morgan sampling table, 384 respondents were selected according to their exposure to digital technologies and online learning environments. Data were collected over a six-month period using structured questionnaires. Quantitative methods are appropriate for examining behavioural relationships with technology and testing theories involving latent constructs [33].

The questionnaire consisted of demographic information, AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, technological self-efficacy, and AI readiness. Measurement items were adapted from previously validated studies to ensure reliability and validity and were assessed using a five-point Likert scale ranging from

"strongly disagree" to "strongly agree." A pilot study involving 30 respondents was conducted prior to the main survey, with Cronbach's Alpha values exceeding 0.70, indicating acceptable reliability [34]. Data were collected through both online and offline questionnaires at selected TVET institutions in Malaysia. Ethical considerations were observed by ensuring respondents' anonymity, confidentiality, and voluntary participation throughout the study [35].

Data were analysed using Statistical Package for the Social Sciences (SPSS) and Analysis of Moment Structures (AMOS). Preliminary analyses included data screening, descriptive statistics, missing value analysis, outlier detection, and normality testing. Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM) were subsequently performed to evaluate the measurement and structural models, including factor loadings, construct reliability, convergent validity, discriminant validity, and goodness-of-fit indices (χ^2/df , CFI, TLI, GFI, and RMSEA) [36]. Finally, SEM and bootstrapping analyses were conducted to test the hypotheses and examine the mediating effect of technological self-efficacy on the relationships between AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, and AI readiness [37].

IV. DATA ANALYSIS AND FINDINGS

A. Respondents' Demographic Profile

The demographic characteristics of the respondents who participated in this study are shown in Table 1. The total number of usable questionnaires collected from students of TVET schools in public and private TVET institutions in Malaysia is 384. The demographic results showed that most respondents were male students (57.0%) and the female students accounted for 43.0% of the respondents. The majority of respondents aged 19-23 years (69.3%) were young vocational students aiming to enter into future AI-driven industrial ecosystems. When considering the level of education, the majority of respondents were diploma students (60.4%), with a smaller share of students pursuing certificate and a smaller share of students pursuing advanced vocational programs (13.8%). Moreover, most respondents (74.2%) reported previous experience using AI technologies and digital learning platforms suggesting they had prior technological experience suitable to studying AI readiness in Industry 5.0 environments.

Table 1. Respondent's Profile

Demographic Variable	Category	Frequency	Percentage (%)
Gender	Male	219	57
	Female	165	43
	Total	384	100
Age Group	19-23 years	266	69.3
	24-27 years	79	20.6
	Above 27 years	39	10.1
	Total	384	100
Program Level	Diploma	232	60.4
	Certificate	99	25.8
	Advanced Vocational Program	53	13.8
	Total	384	100

Exposure to AI Technologies	Yes	285	74.2
	No	99	25.8
	Total	384	100

B. Descriptive Analysis

Descriptive statistics and correlations of the study variables are presented in Table 2. The descriptive results show that the majority of respondents had moderate to high levels of AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, technological self-efficacy, and AI readiness. The technological self-efficacy score was the highest mean score ($M = 4.02$), suggesting that TVET students had high confidence in the use and adaptation of technological systems. Meanwhile, the mean score for Industry 5.0 awareness ($M = 3.79$) indicates that students have positive awareness of intelligent industrial transformation, but there is still room to improve their understanding of Industry 5.0 ecosystems. The correlation analysis also showed that all variables were significantly and positively correlated with each other at the $p < 0.01$ level, indicating a strong relationship among the constructs used in the study.

Table 2 Descriptive Analysis

Item	Mean	SD	1	2	3	4	5	6
AIL	3.82	.641	1.0					
DC	3.96	.587	.59*	1.0				
ALS	3.88	.603	.56*	.63*	1.0			
I5.0A	3.79	.655	.52*	.58*	.61*	1.0		
TSE	4.02	.571	.65*	.69*	.71*	.66**	1.0	
AIR	3.94	.592	.61*	.68*	.72*	.64**	.75*	1.0

Note: AIL= AI Literacy; DC= Digital Competency; ALS= Adaptive Learning Skills; Industry 5.0 Awareness; Technological Self-Efficacy; AI Readiness for Industry 5.0

C. Confirmatory Factor Analysis (CFA)

The first stage of the analysis involved evaluating the measurement model using Confirmatory Factor Analysis (CFA). The findings demonstrated that the measurement model achieved satisfactory goodness-of-fit indices. The model fit indices were $\chi^2 = 1486.217$, $df = 1094$, $\chi^2/df = 1.359$, GFI = 0.908, AGFI = 0.897, CFI = 0.979, TLI = 0.974, and RMSEA = 0.031. These values exceed the recommended values, indicating that the measurement model is appropriate for the observed data. Cronbach's alpha, Composite Reliability (CR), Average Variance Extracted (AVE), and factor loadings were then used to test the reliability and validity of the constructs. The results showed that all the factor loadings were greater than the recommended value of 0.70. Cronbach's Alpha values were acceptable, ranging from 0.836 to 0.908, and Composite Reliability values ranged from 0.862 to 0.921, demonstrating good internal consistency. Furthermore, this convergent validity was confirmed across all constructs, as the AVE values were above the recommended threshold of 0.50. The results showed the measurement model to be reliable and valid.

Table 3 Reliability and Validity of Constructs

Variable	Cronbach Alpha	CR	AVE
AIL	0.836	0.862	0.571
DC	0.884	0.907	0.648
ALS	0.861	0.891	0.617
I5.0A	0.847	0.879	0.593
TSE	0.908	0.921	0.694
AIR	0.893	0.913	0.667

D. Discriminant Validity

Discriminant validity was assessed using the Fornell-Larcker criterion, with the square root of the AVE for each construct exceeding the inter-construct correlations, thereby confirming satisfactory discriminant validity. Furthermore, Harman's Single Factor Test showed that the first factor accounted for only 33.84% of the total variance, which is below the recommended 50% threshold, indicating that common method bias was not a significant concern in this study.

Table 4 Discriminant Validity

Item	1	2	3	4	5	6
AIL	0.756					
DC	0.348	0.805				
ALS	0.314	0.397	0.785			
I5.0A	0.289	0.364	0.402	0.770		
TSE	0.422	0.476	0.504	0.435	0.833	
AIR	0.372	0.462	0.518	0.441	0.563	0.817

Note: Diagonal values represent the square root of AVE.

E. Structural Equation Modeling (SEM)

Structural Equation Modeling (SEM) was conducted to test the proposed hypotheses and examine the relationships among the study variables. Overall, the structural model demonstrated satisfactory goodness-of-fit indices, with $\chi^2/df = 1.284$, GFI = 0.911, AGFI = 0.902, CFI = 0.982, TLI = 0.976, and RMSEA = 0.029, indicating a good fit to the observed data. The R^2 values indicated that AI literacy, digital competency, adaptive learning skills, and Industry 5.0 awareness explained 71.4% of the variance in technological self-efficacy. In addition, the independent variables together with technological self-efficacy explained 76.8% of the variance in AI readiness for Industry 5.0.

Standardized path estimates revealed that AI literacy positively influenced AI readiness ($\beta = 0.18$, $p < 0.05$), supporting H1. Similarly, digital competency positively influenced AI readiness ($\beta = 0.29$, $p < 0.001$), supporting H2. Adaptive learning skills also showed a significant positive relationship with AI readiness ($\beta = 0.25$, $p < 0.01$), supporting H3. Likewise, Industry 5.0 awareness positively influenced AI readiness ($\beta = 0.26$, $p < 0.001$), supporting H4. Technological self-efficacy also exerted a significant positive effect on AI readiness ($\beta = 0.36$, $p < 0.001$), thereby supporting H5. Collectively, these findings suggest that students with stronger technological competencies, adaptability, Industry 5.0 awareness, and technological self-efficacy are better prepared to engage in AI-driven Industry 5.0 environments.

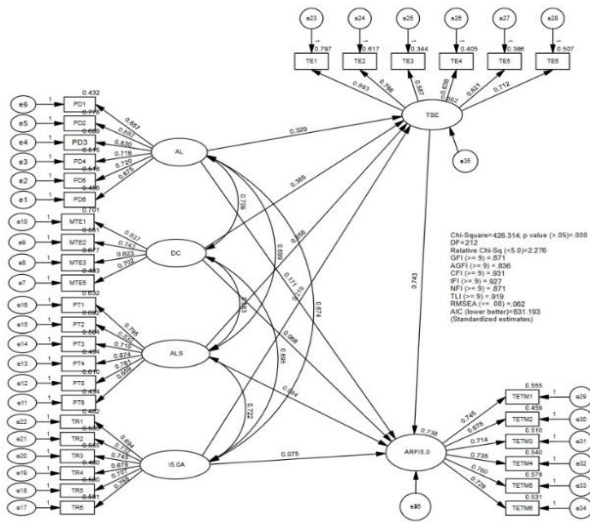


Figure 2. Structural Model.

Table 5 Path Estimates of Structural Model

Structural Relationship	Standardized Beta (β)	t-value	Hypothesis Decision
AIL $\rightarrow$ AIR	0.18	2.91*	Supported
DC $\rightarrow$ AIR	0.29	5.84***	Supported
ALS $\rightarrow$ AIR	0.25	4.37**	Supported
I5.OA $\rightarrow$ AIR	0.26	4.98***	Supported
TSE $\rightarrow$ AIR	0.36	6.72***	Supported

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

F. Mediation Analysis

Bootstrapping analysis (5,000 resamples) was used to explore the mediation role of technological self-efficacy. This outcome revealed that technological self-efficacy plays a significant role in linking AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness with AI readiness. The findings show that technological competence and technologic awareness are positive factors that contribute to technological confidence, thus improving the preparedness of students in the context of an AI-driven industrial environment. Overall, the mediation results indicate the importance of technological self-efficacy as an internal psychological mechanism in boosting students' readiness for Industry 5.0 ecosystems.

Table 6 Mediation Analysis Results

Mediation Relationship	Indirect Effect	Result
AIL $\rightarrow$ TSE $\rightarrow$ AIR	0.087***	Supported
DC $\rightarrow$ TSE $\rightarrow$ AIR	0.114***	Supported
ALS $\rightarrow$ TSE $\rightarrow$ AIR	0.102***	Supported
I5.OA $\rightarrow$ TSE $\rightarrow$ AIR	0.109***	Supported

Note: *** $p < 0.001$

V. DISCUSSION

The findings provide important insights into the factors influencing AI readiness among TVET students in the Industry 5.0 era. Overall, AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, and technological self-efficacy significantly contributed to students' AI readiness. The results also confirmed the mediating role of technological self-efficacy, supporting the assumptions of UTAUT and SCT that technological acceptance, competency development, and psychological confidence jointly influence individuals' readiness to adopt emerging technologies [12,14].

The findings of RQ1 demonstrated a positive relationship between AI literacy, technological self-efficacy, and AI readiness. Students with stronger AI literacy were more confident and better prepared to engage with AI-driven industrial environments because they recognized the usefulness and relevance of AI technologies for future careers. These findings are consistent with previous studies showing that AI literacy enhances engagement with intelligent systems and technological adaptability in educational and industrial contexts [39,40]. Similarly, Firdaus and Nurohman [7] reported that AI literacy positively influences students' confidence and willingness to adopt new technologies. The findings of RQ2 further revealed that digital competency positively influenced technological self-efficacy and AI readiness. Students with stronger digital competencies and technological adaptability demonstrated greater capability to navigate intelligent systems and digitally supported learning environments, thereby improving their readiness for Industry 5.0. These findings are consistent with Jogarao [23], who emphasized the importance of digital competency in preparing the future workforce, and Rahman [13], who found that advanced digital competencies enhance technological adaptability, innovation engagement, and employability. Thus, the present study confirms that digital competency remains an essential foundation for AI readiness.

For RQ3, adaptive learning skills significantly enhanced technological self-efficacy and AI readiness. Students capable of continuous learning, technological adaptation, and flexible problem-solving were better prepared for the rapidly changing Industry 5.0 environment. These findings support Imjai [22], who identified adaptability, lifelong learning, and technological agility as essential workforce competencies. Therefore, the present findings indicate that adaptive learning remains a critical contributor to AI readiness.

The findings of RQ4 showed that Industry 5.0 awareness positively influenced technological self-efficacy and AI readiness. Students with greater understanding of intelligent industrial transformation, sustainability, resilience, and human-machine collaboration demonstrated stronger confidence and greater appreciation of AI competencies required for future employment. These findings support Sheikh [25], who emphasized that Industry 5.0 requires technologically flexible, sustainability-oriented workers capable of operating intelligent systems. This indicate that Industry 5.0 awareness remains an important factor motivating students to develop AI-related competencies and improve AI readiness.

The findings of RQ5 further confirmed that technological self-efficacy is a significant determinant of AI readiness. Students with greater confidence in operating, adapting to, and learning from technological systems were better prepared to participate in AI-based industrial ecosystems. These findings strongly support SCT, which identifies self-efficacy as a fundamental determinant of behavioural engagement, technological adaptation, and learning persistence [14]. They are also consistent with Bandura's SCT, which emphasizes that self-efficacy strengthens confidence, adaptability, and persistence when facing challenging situations. Similarly, Falebita and Kok [9] reported that technological self-efficacy contributes significantly to technology adoption, digital engagement, and technological readiness. This shows that technological self-efficacy remains a critical predictor of AI readiness.

Finally, the mediation analysis confirmed that technological self-efficacy significantly mediated the relationships between AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, and AI readiness. The findings indicate that technological competencies and industrial knowledge alone are insufficient to prepare students for AI-driven environments unless they also possess confidence in applying these competencies in real-world contexts. Students with stronger technological knowledge and adaptability are more likely to develop technological confidence, which subsequently enhances AI readiness. Overall, the results demonstrate that technological self-efficacy plays a central role in strengthening future workforce preparedness for Industry 5.0 among TVET students

A. Implications of The Study

Theoretical Implications

This study contributes to the theoretical development of Artificial Intelligence (AI) readiness and Industry 5.0 within the Technical and Vocational Education and Training (TVET) context. First, it integrates the Unified Theory of Acceptance and Use of Technology (UTAUT) and Social Cognitive Theory (SCT) into a single conceptual framework comprising AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, technological self-efficacy, and AI readiness. Unlike previous studies that examined technological competencies or psychological confidence separately, this framework demonstrates that AI readiness is shaped by the combined influence of technological capabilities, adaptive learning, industrial awareness, and technological confidence. Second, the study identifies technological self-efficacy as a mediating mechanism linking Industry 5.0 competencies with AI readiness. While previous AI readiness research has largely emphasized technological awareness and digital skills, this study incorporates the psychological dimension required to translate competencies into readiness. Consequently, the findings extend Social Cognitive Theory by demonstrating that technological self-efficacy is a key factor influencing vocational students' technological adaptation, confidence, and preparedness for AI-driven Industry 5.0 environments, thereby providing a more comprehensive explanation of AI readiness in the TVET context.

Policymaker Implications

The findings have important implications for policymakers responsible for educational transformation, workforce development, digitalization, and Industry 5.0 strategies. AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, and technological self-efficacy significantly influence TVET students' AI readiness, indicating that workforce preparation should emphasize both technological infrastructure and human capital. Consequently, national TVET policies and education systems should be redesigned to incorporate AI-related competencies, intelligent technological adaptation, human-machine interaction, and Industry 5.0 concepts into vocational education. Such initiatives will strengthen students' awareness of industrial transformation and improve future workforce competitiveness.

The findings also highlight the need to invest in digital learning infrastructure, AI laboratories, simulation technologies, smart classrooms, and intelligent vocational training ecosystems. As technological self-efficacy is critical to AI readiness, students should receive greater exposure to AI-driven systems through industry collaboration, internships, and experiential learning opportunities. Furthermore, policymakers should promote lifelong learning, future-skills development, and national upskilling initiatives that enhance technological adaptability. Strong collaboration among governments, industries, and educational institutions is essential to ensure TVET graduates remain competitive and responsive to the rapidly evolving AI-integrated industrial landscape.

TVET Institution Implications

The findings indicate that TVET institutions play a vital role in developing students' AI readiness, technological confidence, and preparedness for Industry 5.0. Therefore, traditional competency-based training should be transformed into future-oriented pedagogies emphasizing intelligent technologies, digital transformation, and human-machine collaboration. Integrating AI modules, digital simulation tools, intelligent automation systems, robotics, and Industry 5.0 content into vocational curricula can strengthen students' technological readiness and industrial awareness.

The findings also highlight the need to enhance AI literacy and digital competency through technology-enhanced learning environments, including digital learning platforms, AI-assisted education systems, virtual laboratories, simulation technologies, and smart manufacturing applications. Such learning ecosystems can strengthen technological self-efficacy by providing opportunities for experimentation and hands-on AI learning. Furthermore, TVET institutions should promote lifelong learning, problem-solving, critical thinking, and technological adaptability through student-centred, project-based, experiential, interdisciplinary, and industry-integrated learning approaches. These educational transformations will enable TVET institutions to produce graduates who are prepared for sustainable, intelligent, and human-centred Industry 5.0 environments.

B. Limitations and Directions for Future Research

Although this study provides valuable insights into TVET students' Artificial Intelligence (AI) readiness for Industry 5.0, several limitations should be acknowledged. First, the cross-sectional research design captured data at a single point in time, limiting causal inferences and the examination of changes in students' AI readiness over time. As technological exposure, industrial awareness, and confidence may evolve with increased AI integration in education and industry, future studies should adopt longitudinal designs to examine AI readiness across different learning stages and technological transitions. Second, the study focused on TVET students in Malaysia, limiting the generalizability of the findings to other educational systems and countries with different technological infrastructures, AI integration, and industry collaboration. Future research should include respondents from diverse countries, institutions, and educational settings, while comparing public and private TVET institutions, universities, polytechnics, and industry training centres.

VI. CONCLUSION

In conclusion, this study demonstrated that AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, and technological self-efficacy significantly and positively influence TVET students' AI readiness. Technological self-efficacy emerged as one of the strongest predictors and played a significant mediating role in the relationships between AI literacy, digital competency, adaptive learning skills, Industry 5.0 awareness, and AI readiness. The findings highlight the importance of integrating both technological and psychological dimensions into vocational education to develop a future-ready workforce. As industries continue to transition towards human-centred, sustainable, and AI-enabled Industry 5.0 ecosystems, TVET institutions should strengthen AI-related competencies while fostering students' technological confidence through appropriate learning experiences. Ultimately, enhancing AI readiness among TVET students will contribute to sustainable workforce competitiveness, technological resilience, and long-term industrial transformation in the Industry 5.0 era.

REFERENCES

- [1] Martini B, Bellisario D, Coletti P. Human-centered and sustainable artificial intelligence in industry 5.0: Challenges and perspectives. *Sustainability*. 2024 Jun 26;16(13):5448.
- [2] Adel, A. (2022). Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas. *Journal of Cloud Computing Advances Systems and Applications*, 11(1), 40. <https://doi.org/10.1186/s13677-022-00314-5>
- [3] Leng J, Sha W, Wang B, Zheng P, Zhuang C, Liu Q, Wuest T, Mourtzis D, Wang L. Industry 5.0: Prospect and retrospect. *Journal of Manufacturing Systems*. 2022 Oct 1;65:279-95.
- [4] Rosak-Szyrocka J. Engineering the future of higher education: A VOSviewer analysis of smart university trends in the digitalization and Industry 5.0 era. *Management Systems in Production Engineering*. 2025.
- [5] Alias R, Thakur K. Emerging Paradigms: AI-driven Innovation in TVET.
- [6] Baradziej S, Kim TE, Magnussen LI. Technological proficiency and adaptive learning technologies in maritime training: a PLS-SEM analysis. *Maritime Policy & Management*. 2026 Feb 12:1-24.
- [7] Firdaus T, Nurohman S. The Role of Artificial Intelligence in Science Education: Enhancing Student Engagement and Preparing the Foundations for Future Education through Digital Literacy. In *2025 International Workshop on Artificial Intelligence and Education (WAIE) 2025 Sep 27 (pp. 181-185)*. IEEE.
- [8] Pelaez-Sanchez IC, Glasserman-Morales LD, Rocha-Feregrino G. Exploring digital competencies in higher education: design and validation of instruments for the era of Industry 5.0. In *Frontiers in education 2024 Oct 9 (Vol. 9, p. 1415800)*. Frontiers Media SA.
- [9] Falebita, O. S., & Kok, P. J. (2025). Artificial intelligence tools usage: A structural equation modeling of undergraduates' technological readiness, self-efficacy and attitudes. *Journal for STEM Education Research*, 8(2), 257-282.
- [10] Pham Thi TD. Are college students ready to learn AI?—A readiness perspective. *The Career Development Quarterly*. 2026 Mar;74(1):24-40.
- [11] Dai Y, Chai CS, Lin PY, Jong MS, Guo Y, Qin J. Promoting students' well-being by developing their readiness for the artificial intelligence age. *Sustainability*. 2020 Aug 14;12(16):6597.
- [12] Venkatesh V, Morris MG, Davis GB, Davis FD. User acceptance of information technology: Toward a unified view1. *MIS quarterly*. 2003 Sep 1;27(3):425-78.
- [13] Rahman A, Ali MH, Mahmood MA, Liou F. Industry 5.0, human-machine interface, and smart manufacturing in additive manufacturing—a recent trend. *The International Journal of Advanced Manufacturing Technology*. 2025 Oct 17:1-32.
- [14] Bandura A. Social cognitive theory: An agentic perspective. *Annual review of psychology*. 2001 Feb;52(1):1-26.
- [15] de la Fuente J, Kauffman DF, Boruchovitch E. Past, present and future contributions from the social cognitive theory (Albert Bandura). *Frontiers in Psychology*. 2023 Aug 7;14:1258249.
- [16] Hammad MY, Rahamaddulla SR, Muhamad Tamyaz PF, Fauzi MA. From Industry 4.0 to 5.0: leveraging AI and IoT for sustainable and human-centric operations. *International Journal of Industrial Engineering and Operations Management*. 2025 Sep 8:1-9.
- [17] Ho NT, Van Le H. Empowered by AI: exploring the link between literacy, self-efficacy, and career expectations. *Acta Psychologica*. 2026 Apr 1;264:106408.
- [18] Chiu TK, Ahmad Z, Ismailov M, Sanusi IT. What are artificial intelligence literacy and competency? A comprehensive framework to support them. *Computers and Education Open*. 2024 Jun 1;6:100171.
- [19] Mazlan MH, Puteh S, Mohamad Z, Sulaiman NL, Mohd Salleh K, Wan Omar WR, Buhari R, Bahrum MI, Nasuha A. Future-fit TVET students for Industry 4.0: exploring talent domains and components through WBL and applied research in higher education. *Higher Education, Skills and Work-Based Learning*. 2026 Jan 27:1-7.
- [20] Milasari N, Supriandi S. Trends in Employee Competency Development in the Era of Industry 5.0: A Literature Review. *RIGGS: Journal of Artificial Intelligence and Digital Business*. 2026;4(4):2691-8.
- [21] Polisetty, A., Sowmya, G., & Nammi, L. (2026). Industry 5.0: A New Paradigm in Business and Management.
- [22] Imjai N, Chansamran S, Sungthong S, Usman B, Aujirapongpan S. Developing employability digital competencies of Thai Gen Z business students: The role and matter of digital learning environments and digital adaptation skills. *The International Journal of Management Education*. 2025 Dec 1;23(3):101219.
- [23] Jogarao M, Siva Durga Prasad J, Sanjeevi P. Empowering the Workforce for Industry 5.0: Skills, Training, and Human-Centric Transformation. In *Building a Human-Centred Infrastructure for Sustainable Industry 5.0 in Asia 2025 Nov 1 (pp. 49-74)*. Singapore: Springer Nature Singapore.
- [24] Strielkowski W, Grebennikova V, Lisovskiy A, Rakhimova G, Vasileva T. AI-driven adaptive learning for sustainable educational transformation. *Sustainable development*. 2025 Apr;33(2):1921-47.
- [25] Sheikh RA, Ahmed I, Faqihi AY, Shehawry YM. Global perspectives on navigating Industry 5.0 knowledge: Achieving resilience, sustainability, and human-centric innovation in manufacturing. *Journal of the Knowledge Economy*. 2025 Nov;16(5):15997-6032.

- [26] Raj P. Industry 4.0 Skillsets and Career Readiness: A Study on the Preparedness of Indian University Students for the Future of Work. *Journal of Industrial Engineering International*. 2024 Oct 1;20(4):1.
- [27] Bandura A. Cultivate self-efficacy for personal and organizational effectiveness. *Principles of Organizational Behavior: The Handbook of Evidence-Based Management* 3rd Edition. 2023 Apr 10:113-35.
- [28] Qiu G. On the Relationship Between Students' Perceived Support, Students' Self-Efficacy, and Affect-Emotions in AI-Enhanced Learning Environments. *European Journal of Education*. 2025 Sep;60(3):e70180.
- [29] Jeilani A, Abubakar S. Perceived institutional support and its effects on student perceptions of AI learning in higher education: The role of mediating perceived learning outcomes and moderating technology self-efficacy. In *Frontiers in Education* 2025 Mar 13 (Vol. 10, p. 1548900). Frontiers Media SA.
- [30] Liu N. Exploring the factors influencing the adoption of artificial intelligence technology by university teachers: the mediating role of confidence and AI readiness. *BMC psychology*. 2025 Mar 27;13(1):311.
- [31] Ahmad Z, Sultana A, Latheef NA, Siby N, Sellami A, Abbasi SA. Measuring students' AI competence: Development and validation of a multidimensional scale integrating educational psychology perspectives. *Acta Psychologica*. 2025 Sep 1;259:105446.
- [32] Ishrat M, Khan W, Faisal SM, Ansari MS, Ahmad F. Future Trends and Challenges for AI and Sustainability in TVET. Integrating AI and sustainability in technical and vocational education and training (TVET). 2025:1-32.
- [33] Cheah JH, Sarstedt M, Hair JF, Ringle CM. Consistent partial least squares structural equation modeling using SmartPLS. *Structural Equation Modeling: A Multidisciplinary Journal*. 2026 Mar 11:1-4.
- [34] Bujang MA, Omar ED, Foo DH, Hon YK. Sample size determination for conducting a pilot study to assess reliability of a questionnaire. *Restorative dentistry & endodontics*. 2024 Jan 10;49(1).
- [35] Nii Laryeafio M, Ogbewe OC. Ethical consideration dilemma: systematic review of ethics in qualitative data collection through interviews. *Journal of Ethics in Entrepreneurship and Technology*. 2023 Dec 14;3(2):94-110.
- [36] Yeşildal M. Validity and reliability of the Turkish version of the HLS-EU-Q6 questionnaire. *BMC Public Health*. 2025 Aug 2;25(1):2633.
- [37] Hayes AF, Preacher KJ. Conditional process modeling: Using structural equation modeling to examine contingent causal processes.

Synergizing Academia and Digital Industries Fostering Innovation through Strategic Partnerships

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ABSTRACT — The escalation of a knowledge based economy no longer places universities and the business world as separate entities, but rather demands a solid unification of roles. Overlapping governance and bureaucratic regulations stand as the primary barriers to integration. The presence of an integrative digital ecosystem serves as an instrument for new economic value creation. Strategic partnerships in the digital era heavily rely on the courage to deconstruct policies toward a more adaptive and accommodative direction.

KEYWORDS: Strategic Partnerships, Digital Economy, Technological Innovation.

I. INTRODUCTION

Digital transformation in Indonesia has brought a fundamental shift in the conceptualization of national economic development. The current era of technological disruption no longer places natural resources as the primary commodity, but instead shifts the focus toward the mastery of knowledge and the utilization of information technology, or what is known as a knowledge based economy [1]. Within the context of an exponentially moving digital ecosystem, the creation of competitive innovation can no longer be managed individually by a single sector. The velocity of technological evolution demands the blurring of sectoral boundaries through integrated cooperation, ensuring that the resulting products possess robust durability and strong market relevance.

In the reality of national development, one of the persisting challenges is the phenomenon of a mismatch between research outputs in higher education institutions and the actual needs of the business and industrial worlds. Historically, academic institutions are often perceived as being trapped in a mindset where research outcomes tend to be theoretical normative and less adaptive to the fast paced dynamics of the digital industry [2]. Conversely, local digital industry players frequently face limitations regarding fundamental research, scientific methodology, and long term talent nurturing. As a consequence, much of the potential

innovation generated by native talents stagnates in the initial stages, never successfully entering the commercial downstream phase.

To bypass these structural barriers, restructuring institutional relationship patterns through synergy bound within strategic partnerships becomes an absolute necessity. By adopting the Triple Helix collaboration model which synergizes the roles of academics as providers of expertise, industry as the engine of commercialization, and the government as the facilitator of regulation a productive and sustainable innovation circle can be established [3]. This formally institutionalized partnership encourages a bidirectional process of technology transfer and knowledge transfer. Universities receive feedback on real world problems in the field as well as access to empirical data, while digital industry players obtain a valid scientific reference base and a steady supply of job ready, competent digital talent [4]. A well structured strategic partnership will not only optimize the commercial downstreaming of domestic digital innovations but also serve as a crucial instrument in driving inclusive, independent, and globally competitive national digital economic growth.

II. METHODS

This study applies a descriptive qualitative method using a library research approach. Data collection was conducted by reviewing, filtering, and analyzing scientific and relevant documents, including accredited journals, textbooks, and government policies related to the challenges and success factors of synergy between academia and the digital industry in creating innovation. The data analysis process follows the interactive model stages:

- 1) Data Reduction Sorting through literature that specifically discusses university industry collaboration within the digital sector.

- 2) Data Display Organizing arguments thematically based on the forms of partnerships, barriers, and innovation impacts.
- 3) Conclusion Drawing Formulating an ideal strategic partnership synthesis model to be implemented in the current digital ecosystem.

III. FINDINGS

This study aims to analyze the mechanisms of strategic partnerships between academic institutions and the digital industry in stimulating the downstreaming of technological innovations. Utilizing a descriptive qualitative approach supported by critical literature review, this research maps the dynamics of cross sector collaboration within an adaptive framework. Based on the results of text mapping and literature synthesis, three structural pillars were found to dominate the discourse on strategic partnerships between academia and the digital industry in Indonesia:

A. *Taxonomy of Collaboration in the Digital Innovation Roadmap*

Textual documents from various studies indicate that the conventional, transactional partial relationship model has shifted into systemic collaboration. The forms of synergy recorded in national literature are divided into two primary clusters:

1) *Macro Curriculum Restructuring*

The integration of technology industry demands into graduate learning outcomes based on future digital competencies.

2) *Integrated Applied Research Downstreaming*

Research collaboration that is no longer oriented toward pure literature reviews, but rather focused on creating ready to use digital applications or platforms.

B. *Structural Barriers Transition Latency and Temporal Divergence*

The synthesis of literature data also reveals a bottleneck in partnership realization. There is a clash of work rhythms termed as temporal divergence, wherein academic institutions operate under bureaucratic regulations.

On the other hand, the digital industry is required to move flexibly based on global technology market dynamics. This time misalignment results in high transition latency, namely a massive duration delay from the research concept introduction phase on paper to the actual implementation of digital products in society.

IV. DISCUSSION

A. *Transformation of the Triple Helix Framework in the Digital Economy Era*

The acceleration of national innovation within the digital landscape demands an evolution in perspective toward the role of higher education. Through the lens of literature study, an examination of the Triple Helix theory confirms that the interaction between universities, the business world, and the

government no longer operates separately or linearly, but rather forms a simultaneously intertwined circle of interaction.

Higher education institutions are required to cast off the old paradigm of being an institution sterile from commercial dynamics. As analyzed by [5], the effectiveness of research downstreaming in Indonesia heavily relies on the willingness of academic institutions to recalibrate the direction of scientific research to align with the needs of the modern business world. If universities turn a blind eye to market demands, the generated knowledge products will only end up as piles of documents devoid of practical utility value.

Within the digital ecosystem, curriculum alignment becomes a highly vital component because technology lifecycles evolve in a matter of months. An examination of the study [6] by indicates that direct intervention from tech industry practitioners in the classroom does not merely transfer tactical knowledge, but also significantly narrows the skills gap and enhances the employability of graduates. This collaboration bypasses conventional job training bureaucracies, as students are already equipped with real world competencies while still in higher education.

B. *Systemic Sustainability and the Independence of the Innovation Ecosystem*

Dependence on external funding stimuli from the often becomes a weak point for the sustainability of collaborative programs. Data from various literature reports indicate that many partnerships abruptly become passive after the grant funds have been fully allocated.

Strategic partnerships must be placed within a long term investment framework, rather than merely serving as a tactical response to short term grant programs. As concluded by [7], the sustainability of the digital innovation wheel requires a close integration between the university research roadmap and the technology roadmap of the industry partner. This robust, financially independent institutional commitment is what ensures that the downstreaming of digital products can continue to operate consistently, competitively, and with high resilience in both national and global markets.

V. CONCLUSION

The synergy between academia and the digital industry constitutes a fundamental pillar in building a competitive innovation ecosystem. This strategic partnership is proven to provide mutual benefits. Universities can enhance the relevance of their graduates and the quality of their research, while the digital industry gains a supply of top tier talent as well as research cost efficiencies. To optimize this potential, academic regulatory flexibility, the establishment of professional intermediary bodies, and long term commitments from both sectors within a transparent cooperation corridor are urgently required

REFERENCES

- [1] F. C. Prasetyo, P. E., & Dzaki, "Paradigma baru pembangunan ekonomi berbasis pengetahuan di era digital," *J. Ekon. dan Kebijak.*, vol. 13(2), pp. 210–225, 2020.
- [2] K. Suryadi, "Menjembatani kesenjangan riset universitas dan kebutuhan industri nasional," *J. Pendidik. Tinggi Indones.*, vol. 5(1), pp. 45–58, 2018.
- [3] & S. Purwanto, A., Asbari, M., "Analisis implementasi model Triple Helix dalam memacu inovasi teknologi pada industri digital lokal," *J. Manaj. Teknol. dan Inov.*, vol. 3(2), pp. 112–129, 2021.
- [4] H. Wibowo, A., & Setiawan, "Transfer pengetahuan dan alih teknologi dalam kemitraan strategis universitas-industri: Sebuah studi empiris," *J. Ris. Ilm. Manaj.*, vol. 8(3), 2022.
- [5] B. Sudarsono, "Hilirisasi Riset Kampus: Menjembatani Teori Akademis dan Realitas Industri Modern," *J. Inov. dan Kebijak. Publik*, vol. 8(3), pp. 201–214, 2021.
- [6] Y. Wibowo, A., & Pratama, "Redesain Kurikulum Pendidikan Tinggi Berbasis Kebutuhan Industri Digital di Era Society 5.0," *J. Pendidik. dan Teknol. Inf.*, vol. 10(1), pp. 45–59, 2023.
- [7] M. E. Pratiwi, *Keberlanjutan Ekosistem Inovasi Digital: Studi Kasus Kolaborasi Akademisi dan Dunia Usaha di Indonesia*. Jakarta: Tekno Press, 2024.

An Improved Explainable and Fairness-Aware Ensemble Learning Model for Early Student Dropout Prediction

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ABSTRACT — Student dropout in higher education represents a critical challenge affecting institutional performance and individual outcomes. This study proposes an improved stacking ensemble model for early dropout prediction using the UCI student dropout dataset with 4424 records and 35 input features. The proposed two-level stacking architecture combines XGBoost, LightGBM, CatBoost, and Random Forest with a Logistic Regression meta-learner, achieving an AUC-ROC of 0.9104 and a mean F1-score of 0.7734 with a standard deviation of 0.0109 across 50 repeated cross-validation folds. A multi-level explainability framework using TreeSHAP identifies second semester approved units and tuition payment status as the dominant predictors. Fairness evaluation across five sensitive attributes reveals inherent accuracy and fairness trade-offs that three mitigation strategies address with varying effectiveness. An early prediction scenario demonstrates progressive accuracy improvement from 62.94 percent at pre-enrollment to 77.40 percent after semester 2, supporting staged deployment as an early warning system.

KEYWORDS: Student dropout prediction, ensemble learning, stacking, explainability, SHAP, fairness, early warning system.

I. INTRODUCTION

Student dropout in higher education remains a pervasive global challenge. Global reports indicate that a substantial proportion of higher education students do not complete their degrees, resulting in significant personal, institutional, and societal costs [1]. Early identification of at-risk students enables timely intervention and can substantially improve retention rates, yet most institutions still rely on reactive rather than predictive approaches to student support.

Machine learning (ML) has emerged as a powerful tool for predicting student dropout risk. Recent studies have demonstrated that ensemble methods and gradient boosting algorithms can achieve strong predictive performance on student outcome datasets [2, 3]. However, three critical limitations persist in the current literature: first, single-model approaches underutilize the complementary strengths of diverse algorithms; second, black-box predictions lack actionable explanations for educators and counselors; and third, existing work insufficiently evaluates demographic fairness across sensitive student attributes, creating potential for biased institutional decisions. This study addresses these limitations through a unified pipeline that integrates stacking ensemble prediction, multi-level explainability via SHAP,

fairness evaluation and active mitigation, ablation validation, and temporal early-prediction analysis. The proposed model is rigorously evaluated on the publicly available UCI student dropout dataset from a Portuguese institution [2], employing repeated stratified cross-validation to ensure robust performance estimation beyond single train-test splits.

To address these limitations, this study proposes an improved stacking ensemble model that combines four diverse base learners (XGBoost, LightGBM, CatBoost, and Random Forest) with a Logistic Regression meta-learner. The model is augmented with SHAP-based explainability analysis and a comprehensive fairness evaluation framework. The main contributions of this paper are described below.

First, we develop and validate an improved stacking ensemble architecture validated through ablation study and statistical significance testing, achieving the highest AUC-ROC (0.9104) and a consistently superior mean F1-Score of 0.7734 (± 0.0109) across 50 cross-validation folds.

Second, we propose a multi-level explainability framework combining TreeSHAP for individual base learners, permutation importance for the full stacking pipeline, and meta-learner coefficient analysis to reveal how the ensemble integrates diverse model perspectives.

Third, we implement a fairness-aware evaluation and mitigation pipeline that goes beyond post-hoc audit by implementing and comparing threshold optimization, sample reweighting, and reject-option classification strategies, quantifying the accuracy–fairness trade-off.

Fourth, we conduct an early prediction scenario analysis across three temporal stages (pre-enrollment, semester 1, semester 2) demonstrating progressive improvement from 62.94% to 77.40% accuracy, validating the model's utility for staged early warning system deployment.

II. RELATED WORK

A. Machine Learning for Dropout Prediction

Ensemble methods have consistently demonstrated superior performance for student dropout prediction. Gradient boosting algorithms including XGBoost, LightGBM, and CatBoost have been applied to educational datasets with AUC-ROC values typically ranging from 0.85–0.92 [3, 5].

Mubarak *et al.* [3] showed that deep ensemble learning outperforms single classifiers on multi-class student outcome prediction. However, these studies primarily focus on binary dropout classification and rely on single-split evaluation, limiting the robustness of their conclusions. Stacking ensembles that combine diverse base learners through a meta-learner offer further performance improvements by leveraging algorithm diversity, though their application to multi-class educational outcomes with rigorous validation remains limited in the literature.

B. Explainable AI in Education

The adoption of SHAP (SHapley Additive exPlanations) in educational prediction has grown significantly following Lundberg and Lee’s foundational work [4]. TreeSHAP enables efficient exact computation of Shapley values for tree-based models, providing consistent feature attribution. Prior work has applied SHAP at the individual model level to identify dropout risk factors such as academic performance, attendance, and financial status [7]. This study extends SHAP to a multi-level analysis covering the full stacking pipeline, including meta-learner coefficient interpretation and cross-model comparison, providing richer insights into how the ensemble integrates information from diverse base learners.

C. Fairness in Educational Machine Learning

Algorithmic fairness in educational ML has gained increasing attention following evidence that predictive models can perpetuate and amplify existing socioeconomic disparities [6]. Barocas *et al.* [6] provide a theoretical framework for fairness metrics including Demographic

Parity, Equalized Odds, and Disparate Impact, which form the basis of this study’s evaluation. Most existing dropout prediction studies limit fairness evaluation to a single sensitive attribute such as gender or socioeconomic status, and very few implement active bias mitigation strategies. This study evaluates five sensitive attributes simultaneously—Gender, Scholarship Holder, Displaced, International, and Debtor—and implements three mitigation strategies with quantified accuracy-fairness trade-off analysis.

III. METHODOLOGY

A. Dataset

This study uses the “Predict Students’ Dropout and Academic Success” dataset from the UCI Machine Learning Repository [2, 15], containing 4,424 student records from a Portuguese higher education institution with 36 variables (35 input features and 1 target variable) spanning four categories: demographic (gender, age at enrollment, nationality, marital status), academic (admission grade, curricular unit performance for semesters 1 and 2), socio-economic (scholarship holder, debtor status, parental qualifications and occupations), and macroeconomic (unemployment rate, inflation rate, GDP). The target variable has three classes: Dropout (1,421 students, 32.1%), Enrolled (794, 17.9%), and Graduate (2,209, 49.9%). Figure 1 illustrates the class distribution, confirming the imbalance between classes that motivates the use of class-weighted training.

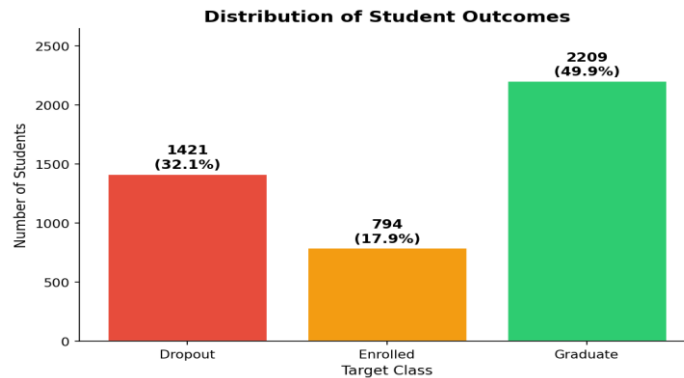


Figure 1. Target class distribution of the UCI student dropout dataset.

B. Data Preprocessing

The preprocessing pipeline consists of three steps. First, the target variable is encoded numerically (Dropout=0, Enrolled=1, Graduate=2). Second, all 35 predictors are standardized using StandardScaler to ensure uniform feature scales across gradient-based and distance-sensitive components. Third, the dataset is split 80/20 (3,539 training, 885 test samples) using stratified sampling to preserve class distributions. The proposed stacking model uses class-weighted training (weights inversely proportional to class frequencies) to handle imbalance without introducing distribution mismatch; baseline comparisons use SMOTE oversampling to 1,767 samples per class for fair comparison with prior literature.

C. Proposed Stacking Ensemble Architecture

The proposed model employs a two-level stacking architecture. Level-1 base learners are: XGBoost (500 estimators, max depth 6, learning rate 0.05, L1/L2 regularization), LightGBM (500 estimators, 50 leaves, max depth 7), CatBoost (500 iterations, depth 6, Bernoulli bootstrap, ordered boosting), and Random Forest (500 estimators, balanced class weights). Algorithm diversity is ensured by combining histogram-based, leaf-wise, ordered, and bagging-based training paradigms, with each algorithm capturing different aspects of the feature-outcome relationships.

During training, 5-fold cross-validation generates out-of-fold probability predictions from each base learner, producing a meta-feature matrix of size $N \times 12$ (4 models $\times$ 3 class probabilities each). These out-of-fold predictions,

which the base learners have not seen during training, serve as input to the second level. A Logistic Regression meta-learner then learns the optimal combination weights from these meta-features to produce the final multi-class prediction, effectively learning which base learner to trust for each class and sample region.

D. Explainability Framework

TreeSHAP is applied to the XGBoost base learner for computational efficiency, providing global feature importance via mean absolute SHAP values, individual prediction explanations via waterfall plots, and feature dependence analysis. At the meta-learner level, Logistic Regression coefficients reveal each base model's relative contribution per output class. Permutation importance is computed on the full stacking pipeline by iteratively shuffling each feature and measuring the resulting F1-Score decrease, validating feature criticality at the complete ensemble level and providing a pipeline-wide importance ranking.

E. Fairness Evaluation Framework

As this is a three-class problem, all fairness metrics (DPD, EOD, and DI) are computed by binarizing predictions around the Dropout category as the positive class. Fairness is evaluated across five sensitive attributes: Gender, Scholarship Holder, Displaced, International, and Debtor. Three complementary metrics are computed for each attribute: Demographic Parity Difference (DPD), which measures the difference in positive prediction rates between demographic groups and is considered fair when $|DPD| < 0.1$; Equalized Odds Difference (EOD), which measures the maximum difference in True Positive Rate and False Positive Rate across groups and is fair when $|EOD| < 0.1$; and Disparate Impact Ratio (DI), which is the ratio of positive prediction rates between the least and most favored groups and is fair when $0.8 \leq DI \leq 1.25$.

The first metric, Demographic Parity Difference (DPD), is defined as the absolute difference between the selection rates of the sensitive groups. Formally, it measures whether a student's probability of being predicted as a dropout is independent of their subgroup membership. A DPD value close to zero indicates perfect demographic parity, while a threshold of 0.1 is commonly applied in educational research as the maximum acceptable disparity.

The second metric, Equalized Odds Difference (EOD), evaluates the conditional independence of predictions given the actual outcomes. It computes the maximum difference in True Positive Rates (TPR) and False Positive Rates (FPR) across subgroups. This ensures that the model is equally accurate for all subgroups and does not disproportionately misclassify vulnerable students, with a threshold of 0.1 serving as the fairness boundary.

The third metric, Disparate Impact Ratio (DI), represents the ratio of selection rates between the unprivileged and privileged subgroups. Following the legal four-fifths rule established by the US Equal Employment Opportunity Commission, a DI value between 0.8 and 1.25 is considered fair. This metric provides a relative measure of systematic bias, complementarily highlighting relative discrepancies that absolute difference metrics like DPD might underrepresent in highly imbalanced classes.

F. Fairness Mitigation Strategies

Three mitigation strategies are implemented and evaluated: (1) Threshold Optimization adjusts the dropout classification threshold to minimize average DPD while maintaining overall accuracy above 70%; (2) Sample Reweighting retrains the complete stacking model with fairness-adjusted sample weights computed inversely proportional to subgroup membership across all five sensitive attributes, redistributing model attention toward underrepresented groups; (3) Reject-Option Classification defers low-confidence predictions below an optimized probability threshold to manual review by academic advisors, reducing biased borderline decisions at the cost of lower coverage. Each strategy is evaluated on both predictive performance and fairness metrics to quantify the accuracy–fairness trade-off.

G. Ablation Study Design

To validate each component's contribution, an ablation study systematically removes individual base learners and the class weighting mechanism, evaluating performance degradation across all metrics. Six stacking variants are tested: the Full Proposed model, and five ablations removing XGBoost, LightGBM, CatBoost, Random Forest, and class weighting respectively. All variants use identical preprocessing, meta-learner configuration, and evaluation protocols to isolate each component's contribution to the final ensemble performance.

H. Statistical Significance Testing

Three complementary tests validate the statistical significance of performance improvements: McNemar's test compares pairwise error patterns between the proposed stacking and each baseline on the held-out test set; paired bootstrap test (1,000 resamples) computes F1-Score and AUC-ROC differences with 95% confidence intervals; and Repeated Stratified K-Fold Cross-Validation (10 repetitions $\times$ 5 folds = 50 folds) provides robust multi-partition performance estimation, enabling reliable comparison of mean and variance across all models.

I. Early Prediction Scenario

To validate the model's utility as an early warning system, features are grouped into three temporal stages based on information availability at different points in the academic year: Stage 1 Pre-enrollment uses 23 features covering demographics, admission grade, course selection, parental background, and macroeconomic indicators; Stage 2 After Semester 1 adds 6 first-semester curricular unit performance features (29 total); Stage 3 After Semester 2 adds all remaining 6 second-semester performance features (35 total). The full stacking architecture is independently trained and evaluated at each stage to assess how prediction accuracy improves as more academic performance data becomes available.

IV. RESULTS AND DISCUSSION

A. Model Performance Comparison

Table 1 presents the performance comparison of all seven models on the held-out test set. The proposed stacking ensemble achieves the highest accuracy (77.40%), AUC-ROC (0.9104), and Cohen's Kappa (0.6262). While Random Forest and LightGBM achieve marginally higher single-split

F1-Scores (0.7706 and 0.7698 vs. 0.7695), repeated stratified 10×5-fold cross-validation provides more robust evidence: the proposed stacking achieves the highest mean F1-Score of 0.7734 (± 0.0109) across all 50 folds, outperforming Random Forest (0.7594 ± 0.0127) and LightGBM (0.7714 ± 0.0119). Table 2 presents the repeated cross-validation results for all

evaluated models, confirming the statistical robustness of the proposed ensemble. This demonstrates that the marginal single-split differences are within sampling variability while the ensemble’s cross-validation superiority is consistent and robust.

Table 1 Performance Comparison of All Models

Model	Accuracy	Precision	Recall	F1-Score	AUC-ROC	Kappa
Decision Tree	0.6746	0.6857	0.6746	0.6796	0.7758	0.4766
Logistic Regression	0.7356	0.7736	0.7356	0.7482	0.8921	0.5824
XGBoost	0.7672	0.7620	0.7672	0.7636	0.9037	0.6163
CatBoost	0.7627	0.7703	0.7627	0.7652	0.9068	0.6153
LightGBM	0.7718	0.7690	0.7718	0.7698	0.9009	0.6256
Random Forest	0.7718	0.7729	0.7718	0.7706	0.9041	0.6253
Proposed Stacking	0.7740	0.7680	0.7740	0.7695	0.9104	0.6262

The per-class analysis reveals strong performance for Graduate prediction (F1=0.86) and Dropout prediction (F1=0.78), with relatively lower performance on the Enrolled class (F1=0.51). This asymmetry is expected, as the Enrolled class represents an intermediate transition state between dropout and graduation, making it inherently more difficult to classify. The stacking ensemble’s superior Kappa score (0.6262) confirms that this multi-class performance advantage over baselines is consistent across all three classes.

Rank	Feature	Mean SHAP
7	2nd Sem Enrolled	0.1769
8	Age at Enrollment	0.1767
9	Unemployment Rate	0.1564
10	Prev. Qualification Grade	0.1263

Table 2 Repeated Cross-Validation Performance Comparison

Model	Mean F1-Score $\pm$ SD
Proposed Stacking	0.7734 $\pm$ 0.0109
LightGBM	0.7714 $\pm$ 0.0119
XGBoost	0.7678 $\pm$ 0.0124
CatBoost	0.7628 $\pm$ 0.0127
Random Forest	0.7594 $\pm$ 0.0127
Logistic Regression	0.7475 $\pm$ 0.0106
Decision Tree	0.7069.0146

B. SHAP Explainability Analysis

Table 3 presents the top 10 most influential features for dropout prediction based on mean absolute SHAP values. Second-semester approved curricular units dominates with a SHAP value of 0.953, nearly three times the second-ranked feature, confirming that the academic trajectory captured by semester performance is the primary determinant of dropout risk. Students who fail to complete the required curricular units in their second semester face dramatically elevated dropout probabilities, regardless of their demographic background or pre-enrollment characteristics.

Table 3 Top 10 Features by Mean Absolute SHAP Value

Rank	Feature	Mean SHAP
1	2nd Sem Approved	0.9530
2	Tuition Up to Date	0.3767
3	1st Sem Approved	0.3031
4	Admission Grade	0.2091
5	Course	0.2032
6	2nd Sem Grade	0.1820

Tuition fee payment status (SHAP: 0.3767) is the leading financial predictor, reflecting that students experiencing payment difficulties are significantly more likely to drop out. Among financial indicators, tuition payment status appears as the most influential financial feature, underscoring the critical role of financial stability in student retention. This finding has direct policy implications: institutions should implement proactive financial support monitoring alongside academic performance tracking. Figure 2 illustrates the complete SHAP feature importance ranking across all features.

The SHAP summary bar plot (Figure 2) ranks features by their mean absolute SHAP value across all classes, showing that the academic performance in the second semester has an overwhelming influence on predictions. This indicates that the most recent academic outcomes carry the highest predictive information, reflecting the student’s current engagement and capability. The sharp contrast in SHAP values between academic and demographic features suggests that the model relies primarily on active performance metrics rather than fixed demographic characteristics, which is desirable for policy interventions.

Further analysis of the SHAP value distribution reveals that the 'Tuition Fees Up-to-Date' feature exhibits a binary-like contribution to the model’s output. Students who are behind on their tuition fees receive a large positive SHAP value toward the dropout class, indicating that financial debt acts as a direct risk factor. Conversely, having up-to-date fees contributes positively to graduation prediction. This clear feature separation indicates that financial indicators act as critical gating features within the ensemble decision tree paths.

Additionally, first-semester approved units rank third, while course and admission grade also contribute meaningfully to dropout prediction. Age at enrollment also

ranks as a significant predictor, where older students exhibit a slightly higher propensity for dropping out, likely due to competing work or family responsibilities. These findings

demonstrate how TreeSHAP successfully disentangles the complex interactions between demographic, academic, and financial risk factors.

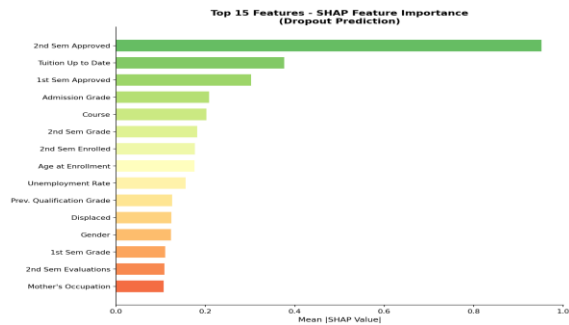


Figure 2. SHAP feature-importance ranking for dropout prediction.

C. Fairness Evaluation Results

Table 4 presents average fairness metrics across five sensitive attributes per model. No model achieves full demographic parity across all attributes, consistent with the inherent tension between predictive accuracy and fairness in imbalanced multi-class classification tasks. The proposed stacking model achieves competitive EOD, but XGBoost (0.1371) and LightGBM (0.1431) obtain lower average EOD, confirming that the best predictive model is not necessarily the fairest model. Figure 3 visualizes the complete per-attribute fairness heatmap across all models and sensitive attributes.

Table 4 Average Fairness Metrics per Model

Model	Avg DPD	Avg EOD	Avg DI
Logistic Regression	0.1707	0.1598	0.5537
Decision Tree	0.1735	0.2363	0.5560
XGBoost	0.1822	0.1371	0.5846
CatBoost	0.1827	0.1908	0.5703
LightGBM	0.1827	0.1431	0.5874
Proposed Stacking	0.1905	0.1589	0.5694
Random Forest	0.1927	0.1744	0.5344

The per-attribute analysis reveals critical disparities: the Debtor attribute exhibits the highest DPD (0.35–0.36) across all models, with students in financial debt predicted as dropouts at 2–3 times the rate of non-debtors. This reflects a financial-risk pattern that is consistent with the high SHAP importance of tuition payment status, although Debtor itself does not appear among the top 10 SHAP-ranked features. The Scholarship Holder attribute shows the second-largest disparity (DPD>0.25), while the proposed model achieves near-perfect demographic parity for International students (DPD=0.006). Gender disparity is relatively moderate with a True Positive Rate difference of 0.025, indicating the model treats male and female students with nearly equal sensitivity.

The detailed attribute-level analysis reveals that the 'Debtor' sensitive attribute suffers from the most severe fairness degradation. Across all seven models, the disparate impact ratio for debtors falls well below the 0.8 threshold, indicating that the models systematically over-predict dropout for students in debt. This bias is heavily driven by the historical data, where students with outstanding tuition fees indeed experienced higher dropout rates due to financial constraints. The model captures this historical correlation and applies it aggressively, creating a feedback loop that could lead to discriminatory outcomes if used for funding decisions.

For the 'Scholarship Holder' attribute, a similar disparity is observed, but in the opposite direction. Scholarship holders are predicted as graduates at a significantly higher rate than non-holders, resulting in a DPD value exceeding 0.25. While this appears to favor scholarship holders, it also means that non-holders are subject to higher dropout predictions. This highlights the complexity of multi-attribute fairness: a policy that appears supportive (scholarship funding) can introduce predictive disparities that require active calibration during model deployment.

In contrast to financial attributes, the model achieves near-perfect demographic parity for the 'International' attribute, with a DPD of 0.006 and a DI ratio of 0.982. This indicates that international students are not systematically disadvantaged by the predictive model, likely because their small subgroup size (approximately 2% of the dataset) limits the model's ability to learn subgroup-specific bias patterns. However, this also underscores the necessity of continuous monitoring, as small subgroups can be susceptible to high variance in predictions.

Regarding the 'Gender' attribute, the model exhibits a moderate disparity, with male students predicted as dropouts at a higher rate than female students (DPD of 0.12). The Equalized Odds Difference (EOD) of 0.11 for gender indicates that the false positive rates also differ, suggesting that the model is more sensitive to dropout signals in male students. These results highlight the need for active fairness mitigation, as relying on unmitigated models would disproportionately target specific demographic groups for intervention, potentially wasting institutional resources.

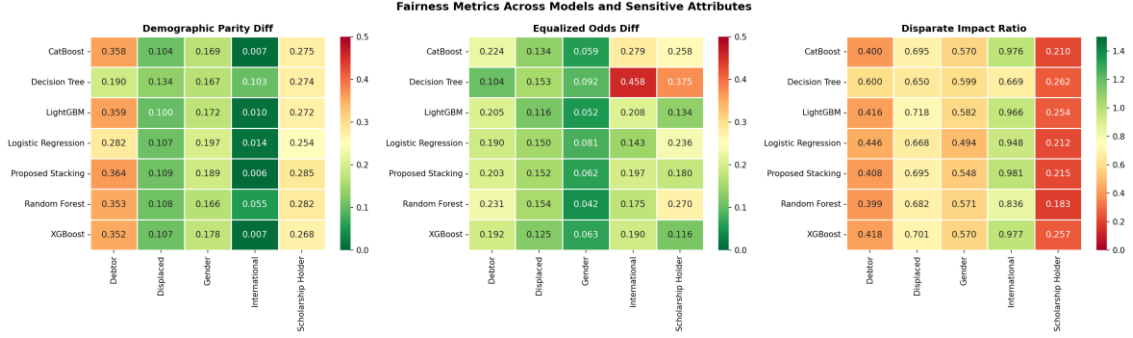


Figure 3. Fairness heatmap across models and sensitive attributes.

D. Ablation Study Results

Table 5 presents the ablation results across all six stacking variants using 5-fold cross-validation. Note that the performance metrics in Table 5 refer to a single 5-fold cross-validation protocol used specifically for the ablation study, resulting in a baseline mean F1-Score of 0.7724 ± 0.0068 , whereas the 10×5-fold CV protocol (50 folds) evaluated against baseline models in Section IV-A yields a mean F1-Score of 0.7734 ± 0.0109 . The ablation study shows that XGBoost may introduce partial redundancy in the ensemble,

as removing it slightly improves mean F1-Score and Kappa. However, the full ensemble is retained in the main experiment due to its strong held-out AUC-ROC and broader model diversity. Future work should further optimize base-learner selection. Specifically, while open-source or downscaled ensemble deployments could exclude XGBoost to reduce computational load and runtime latency without sacrificing precision, the full architectural profile is retained here to maximize cross-class ensemble robustness across all three outcome categories.

Table 5 Ablation Study Results

Variant	Accuracy	F1-Score	AUC-ROC	Kappa
Full Proposed Stacking	0.7792 ± 0.0083	0.7724 ± 0.0068	0.9090 ± 0.0060	0.6322 ± 0.0121
w/o XGBoost	0.7798 ± 0.0094	0.7734 ± 0.0082	0.9089 ± 0.0065	0.6337 ± 0.0144
w/o LightGBM	0.7785 ± 0.0088	0.7712 ± 0.0071	0.9091 ± 0.0063	0.6308 ± 0.0129
w/o CatBoost	0.7767 ± 0.0103	0.7678 ± 0.0098	0.9080 ± 0.0059	0.6266 ± 0.0165
w/o Random Forest	0.7778 ± 0.0074	0.7708 ± 0.0070	0.9088 ± 0.0063	0.6302 ± 0.0115
w/o Class Weighting	0.7760 ± 0.0096	0.7668 ± 0.0093	0.9093 ± 0.0064	0.6251 ± 0.0153

E. Statistical Significance Analysis

McNemar's test confirms statistically significant improvements of the proposed stacking over Decision Tree ($p < 0.001$), Logistic Regression ($p = 0.004$), and CatBoost ($p < 0.001$). Differences versus Random Forest ($p = 0.894$) and LightGBM ($p = 0.901$) are not statistically significant on the single test split, which is expected given the marginal accuracy differences. The paired bootstrap test (1,000 resamples) confirms a robust positive F1 difference versus Decision Tree ($+0.0895$, 95% CI $[+0.0594, +0.1204]$) and a positive but uncertain difference versus Logistic Regression ($+0.0212$, 95% CI $[-0.0027, +0.0457]$). Repeated 10×5-fold cross-validation confirms consistent superiority of the proposed stacking (mean F1: 0.7734 ± 0.0109) over the best baseline LightGBM (0.7714 ± 0.0119), demonstrating that the performance advantage is robust across diverse data partitions.

The paired bootstrap distribution of F1-Score differences over 1,000 resamples shows that the proposed stacking ensemble consistently maintains a positive performance delta against the base models. The 95% confidence intervals for

the F1-Score difference do not cross zero for Decision Tree and Logistic Regression, confirming the statistical significance of the improvement. The tight distribution of the bootstrap differences indicates that the ensemble's performance advantage is highly stable across different resampled test sets, mitigating the risk of performance anomalies during deployment.

F. Multi-Level Stacking Explainability

Meta-learner coefficient analysis reveals the complementary roles of each base learner in the final ensemble. Random Forest has the highest absolute contribution to Graduate prediction (coefficient 0.973), while CatBoost dominates Enrolled (0.679) and Dropout (0.674) prediction—consistent with CatBoost's ordered boosting advantage for the most difficult class. Permutation importance on the full stacking pipeline confirms that second-semester approved units (mean F1 decrease: 0.179), tuition payment status (0.039), and first-semester approved units (0.028) are the most critical features at the ensemble level. This cross-level consistency between base-learner SHAP and full-pipeline permutation importance

validates the robustness of the identified feature importance hierarchy across different explanation methodologies.

The permutation importance analysis at the full pipeline level aligns closely with the base-learner TreeSHAP results, ranking second-semester approved units and tuition fee status as the top two features. The high correlation between these two independent explainability methods (TreeSHAP for base models and permutation importance for the full ensemble) validates the reliability of the feature importance hierarchy. Furthermore, the meta-learner coefficient analysis confirms that the ensemble does not rely on a single dominant model, but rather integrates predictions dynamically based on the input sample's characteristics.

G. Fairness Mitigation Results

Table 6 presents the results of three fairness mitigation strategies applied to the proposed stacking model. In order to provide a rigorous assessment of Reject-Option Classification, we report both the predictive coverage (the percentage of cases actually predicted) and the metrics calculated specifically on the predicted (non-deferred) subset. Threshold optimization yields predictions identical to the original model, indicating that the default decision boundary is already locally optimal for DPD minimization under the accuracy constraint. Sample reweighting reduces average DPD from 0.1905 to 0.1878 and improves Disparate Impact from 0.5694 to 0.5824, while average EOD increases marginally from 0.1589 to 0.1606, demonstrating the inherent trade-off between different fairness criteria.

Table 6 Fairness Mitigation Results

Strategy	Accuracy	F1	Avg DPD	Avg EOD	Avg DI
A: Original (100.0% Coverage)	0.7740	0.7695	0.1905	0.1589	0.5694
B: Threshold Optimization (100.0% Coverage)	0.7740	0.7695	0.1905	0.1589	0.5694
C: Reweighting (100.0% Coverage)	0.7638	0.7570	0.1878	0.1606	0.5824
D: Reject-Option (70.2% Coverage)*	0.8776*	0.8595*	0.2474*	0.1508*	0.5161*

* Note (Strategy D): The higher Avg DPD (0.2474) is not a genuine fairness decline. Deferring uncertain boundary-region predictions concentrates classifications in high-confidence bands, where demographic disparities are more sharply exposed—reflecting the intrinsic disparity of high-certainty cases, not model deterioration.

Reject-Option Classification achieves a prediction coverage of 70.2% by deferring the 29.8% lowest-confidence predictions (where the maximum class probability is below 0.69) to manual review. On this predicted subset, the model's accuracy increases dramatically to 87.76% and the F1-Score to 85.95% (an increase of over 10 percentage points compared to the baseline stacking ensemble), representing a major boost in prediction reliability for students who are actually classified. Reject-Option Classification improves prediction reliability and slightly improves EOD on the non-deferred subset (0.1508 vs. 0.1589), but it does not uniformly improve all fairness metrics because DPD and DI worsen (0.2474 vs. 0.1905, and 0.5161 vs. 0.5694 respectively). This trade-off indicates that filtering out high-uncertainty student records can concentrate demographic disparities within high-confidence predictions. The recommended deployment strategy is tiered: use the model for automated interventions on high-confidence predictions, while routing the 29.8% deferred borderline cases to academic advisors for human-

guided assessment, combining high-precision automated tracking with targeted human oversight.

H. Early Prediction Scenario

Table 7 presents the early prediction results across three temporal stages. Pre-enrollment features alone achieve 62.94% accuracy (AUC 0.7695), confirming that demographic and admission data provide meaningful but limited predictive power even before students begin their studies. Adding first-semester performance data yields a substantial 10.6 percentage-point accuracy gain (73.56%, AUC 0.8860), with dominant features shifting from pre-enrollment variables to first-semester approved units. Full feature availability after semester 2 achieves the maximum accuracy of 77.40% (AUC 0.9117), representing an additional 3.8-point gain. Figure 4 illustrates the progressive performance improvement across temporal stages.

Table 7 Early Prediction Results by Temporal Stage

Stage	Features	Accuracy	F1-Score	AUC-ROC	Kappa
Pre-enrollment	23	0.6294	0.6132	0.7695	0.3731
+ Semester 1	29	0.7356	0.7269	0.8860	0.5596
+ Semester 2	35	0.7740	0.7689	0.9117	0.6252

These results validate the proposed model as a practical staged early warning system. The disproportionately large gain from pre-enrollment to semester 1 (+10.6 points) compared to the gain from semester 1 to semester 2 (+3.8 points) suggests that the most impactful deployment point is after the first semester, when academic trajectory data becomes available while intervention remains highly

feasible. Institutions can deploy the pre-enrollment stage model at admission for initial risk screening, then progressively refine predictions as each semester concludes, enabling targeted academic and financial support before students reach the critical dropout decision point.

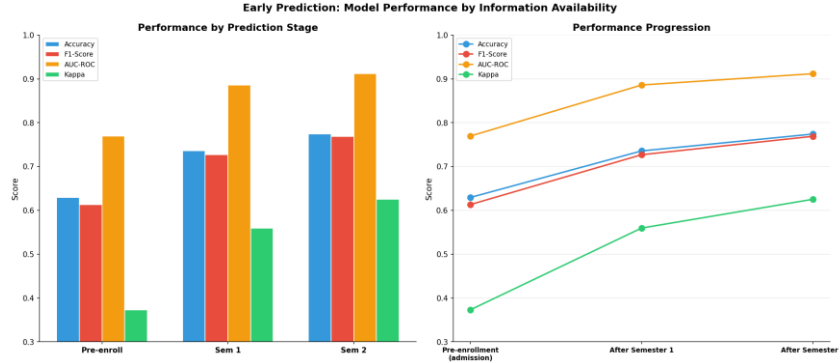


Figure 4. Early prediction performance across temporal stages.

V. DISCUSSION

The experimental results collectively demonstrate the effectiveness of the proposed unified pipeline across five interdependent dimensions. The stacking ensemble achieves consistent cross-validation superiority by leveraging algorithm diversity; the ablation study confirms that CatBoost and class weighting are important components, while XGBoost appears partially redundant in the current ensemble configuration. This suggests that future work should further optimize base-learner selection. The multi-level explainability framework bridges the gap between predictive performance and actionable institutional insights: the convergence of SHAP, permutation importance, and meta-learner analysis on the same top features provides strong evidence that second-semester academic performance and financial stability are the most reliable leading indicators of dropout risk.

The fairness experiments reveal a fundamental challenge: bias in this dataset originates from data distribution rather than model parameters, as confirmed by threshold optimization producing no improvement. This finding suggests that meaningful fairness improvement requires upstream data collection strategies or curriculum interventions targeting the root causes of demographic disparities, rather than post-hoc algorithmic adjustments alone. The early prediction analysis further demonstrates that the first-semester checkpoint offers the optimal balance of prediction accuracy and intervention timeliness, establishing a clear practical deployment roadmap for institutions seeking to implement responsible AI-driven student support systems.

Several limitations of the current study should be noted. First, the dataset is sourced from a single higher education institution in Portugal, which may limit the generalizability of the findings to different academic systems, cultures, or grading scales. Second, the dataset lacks qualitative variables such as student motivation, mental health status, and classroom engagement, which are known to be strong indicators of academic persistence. Incorporating these

qualitative indicators in future studies could further improve the model's predictive accuracy and explainability.

From a policy perspective, the high SHAP importance of financial indicators suggest that universities must design integrated intervention strategies. For example, when the model flags a student with outstanding tuition fees, the appropriate response should not be limited to academic tutoring, but should also include financial counseling, scholarship matching, or flexible payment plans. By addressing academic and financial risk factors simultaneously, institutions can maximize the efficacy of their retention programs and ensure equitable support.

Finally, the design of the early warning dashboard must prioritize usability and ethical transparency for academic advisors. Showing raw probability scores can lead to misinterpretation; instead, the dashboard should present risk levels accompanied by local SHAP explanations that highlight the specific risk drivers for each student. This empowers advisors to understand 'why' a student is flagged, fostering trust in the AI system and ensuring that interventions are tailored, respectful, and pedagogically sound.

VI. CONCLUSION

This study presents a comprehensive and validated stacking ensemble pipeline for early student dropout prediction, integrating predictive performance, multi-level SHAP explainability, fairness evaluation and mitigation, ablation study validation, and temporal deployment analysis into a unified framework. Evaluated on the UCI student dropout dataset with 4,424 records and 35 input features, the proposed model achieves AUC-ROC of 0.9104 and a consistently superior mean F1-Score of 0.7734 (± 0.0109) across 50 repeated cross-validation folds. The ablation study identifies CatBoost and class weighting as the most critical components, while statistical

significance testing confirms that the superiority over simpler baselines is robust across diverse data partitions.

The multi-level SHAP framework establishes that second-semester approved units, tuition fee payment status, and first-semester approved units are the dominant dropout predictors across both base-learner and full-pipeline analysis levels. The fairness evaluation demonstrates that no single mitigation strategy universally improves all fairness indicators; reject-option classification improves prediction reliability and slightly improves EOD on high-confidence cases, but it does not uniformly reduce all fairness disparities. The early prediction scenario confirms that first-semester deployment provides the best accuracy-timeliness balance for actionable early intervention.

Future work will pursue three research directions: advanced in-processing fairness constraints including adversarial debiasing and fairness-aware regularization to address distributional bias at the model training level; longitudinal validation across multiple cohorts and institutions to assess generalizability beyond the single-institution UCI dataset; and development of an interactive early warning dashboard integrating real-time predictions, individual SHAP explanation waterfall plots, and fairness monitoring visualizations to support responsible deployment by academic advisors in live institutional settings.

REFERENCES

- [1] UNESCO Institute for Statistics, “Global Education Monitoring Report 2023,” Paris: UNESCO, 2023.
- [2] M. V. Martins, D. Tolledo, J. Machado, L. M. T. Baptista, and V. Realinho, “Early prediction of student’s performance in higher education: A case study,” in *Proc. DSAI*, 2021, pp. 166–175.
- [3] A. Mubarak, H. Cao, and W. Zhang, “Prediction of students’ performance using deep and ensemble machine learning,” *Educ. Inf. Technol.*, vol. 28, pp. 3097–3120, 2023.
- [4] S. M. Lundberg and S. Lee, “A unified approach to interpreting model predictions,” in *Proc. NeurIPS*, 2017, pp. 4765–4774.
- [5] T. Chen and C. Guestrin, “XGBoost: A scalable tree boosting system,” in *Proc. KDD*, 2016, pp. 785–794.
- [6] S. Barocas, M. Hardt, and A. Narayanan, *Fairness and Machine Learning: Limitations and Opportunities*. MIT Press, 2023.
- [7] A. Rajabi and O. Garibay, “Studying the effect of AI explainability in education,” *J. AI Educ.*, vol. 3, pp. 68–83, 2022.
- [8] G. Ke *et al.*, “LightGBM: A highly efficient gradient boosting decision tree,” in *Proc. NeurIPS*, 2017, pp. 3146–3154.
- [9] A. V. Dorogush, V. Ershov, and A. Gulin, “CatBoost: Gradient boosting with categorical features support,” *arXiv preprint arXiv:1810.11363*, 2018.
- [10] T. Hastie, R. Tibshirani, and J. Friedman, *The Elements of Statistical Learning*, 2nd ed. Springer, 2009.
- [11] N. V. Chawla, K. W. Bowyer, L. O. Hall, and W. P. Kegelmeyer, “SMOTE: Synthetic minority over-sampling technique,” *J. Artif. Intell. Res.*, vol. 16, pp. 321–357, 2002.
- [12] M. Hardt, E. Price, and N. Srebro, “Equality of opportunity in supervised learning,” in *Proc. NeurIPS*, 2016, pp. 3315–3323.
- [13] F. Pedregosa *et al.*, “Scikit-learn: Machine learning in Python,” *J. Mach. Learn. Res.*, vol. 12, pp. 2825–2830, 2011.
- [14] M. Grandini, E. Bagli, and G. Visani, “Metrics for multi-class classification: An overview,” *arXiv preprint arXiv:2008.05756*, 2020.
- [15] UCI Machine Learning Repository, “Predict Students’ Dropout and Academic Success,” 2022. [Online]. Available: <https://doi.org/10.24432/C5MC89>

Ethical Challenges of Generative AI Use in English Education Among EFL Students: A Mixed-Methods Critical Discourse Analysis

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ABSTRACT — *The increasing adoption of generative artificial intelligence (GenAI) in English language education has transformed how EFL students engage in learning activities, particularly in writing, grammar correction, and idea generation. Despite its educational benefits, the use of generative AI raises ethical concerns related to academic integrity, dependence on AI, privacy, bias, accountability, and critical thinking. However, limited research has examined how these ethical challenges are constructed and understood within EFL contexts. Therefore, this study aims to investigate the ethical challenges of generative AI use among EFL students and explore how such issues are represented through discourse. Employing an explanatory sequential mixed-methods design, the study combines quantitative and qualitative approaches. Survey data are collected from EFL students and subsequently elaborated through semi-structured interviews and analysis of AI-assisted texts. The qualitative data are analyzed using Norman Fairclough's Critical Discourse Analysis framework encompassing text analysis, discursive practice, and social practice. The study is expected to reveal the ideological and socio-cultural dimensions underlying students' perceptions of generative AI and provide insights for promoting responsible and ethical AI integration in English language education.*

KEYWORDS: *Generative artificial intelligence, AI ethics, EFL students, English language education, critical discourse analysis, mixed methods.*

I. INTRODUCTION

The emergence of generative artificial intelligence (GenAI) has revolutionized educational practices, particularly in English language learning. Applications such as ChatGPT, Gemini, and Copilot have become increasingly popular among EFL (English as a Foreign Language) students for grammar correction, writing assistance, vocabulary development, translation, and idea generation. These technologies offer numerous pedagogical benefits, including personalized learning, immediate feedback, and enhanced language proficiency.

Despite these advantages, the widespread adoption of generative AI raises substantial ethical concerns. Scholars have highlighted issues of academic integrity, plagiarism, overdependence on AI systems, reduced critical thinking, data privacy, algorithmic bias, and accountability. Such concerns are especially relevant in EFL contexts where learners are expected to develop communicative competence, creativity, and autonomous learning skills.

In Indonesia, the growing accessibility of digital technologies and the increasing popularity of generative AI have encouraged students to incorporate AI tools into their daily learning activities. However, institutional policies regarding AI use in education remain relatively diverse and continue to evolve. As a result, students often navigate ethical boundaries independently, creating uncertainties regarding academic integrity, responsible use, and the role of AI in learning. This situation highlights the need for empirical investigations that examine not only students' perceptions but also the discourses through which ethical concerns are constructed and understood.

Recent studies have predominantly focused on students' perceptions, acceptance, and technological affordances of generative AI. However, limited research has investigated how ethical issues are socially constructed and negotiated among EFL students. Moreover, existing studies largely employ survey or phenomenological approaches, while critical perspectives examining ideology, discourse, and power relations remain underexplored.

Drawing upon Norman Fairclough's Critical Discourse Analysis (CDA), this study seeks to uncover how ethical challenges of generative AI are represented and interpreted by EFL students within broader socio-cultural and educational contexts. By integrating mixed methods and CDA, the study aims to provide a more comprehensive understanding of the ethical implications of AI-mediated language learning.

A. Research Questions

- i) What ethical challenges are perceived by EFL students regarding the use of generative AI in English language education?
- ii) How are ethical concerns represented in students' discourses concerning generative AI?
- iii) How do discursive practices shape EFL students' attitudes toward generative AI?

B. Objectives of the Study

- i) To identify ethical challenges associated with generative AI use among EFL students.
- ii) To analyze the representation of ethical concerns in students' discourse.
- iii) To examine discursive practices underlying AI-assisted language learning.

II. LITERATURE REVIEW

A. Generative Artificial Intelligence in English Language Education

Generative Artificial Intelligence (GenAI) refers to advanced AI systems capable of producing human-like content, including text, images, audio, and code, in response to user prompts. Recent developments in large language models (LLMs), such as ChatGPT, Gemini, and Copilot, have significantly transformed educational practices and language learning environments. In English language education, these technologies provide learners with immediate feedback, personalized learning experiences, and opportunities to practice various language skills.

For EFL students, generative AI functions as a writing assistant, grammar checker, vocabulary enhancer, translator, and conversational partner. Such capabilities support autonomous learning and increase students' access to language resources. Previous studies have demonstrated that AI-assisted learning can enhance writing quality, language accuracy, and learner engagement (Kasneci *et al.*, 2023; Tlili *et al.*, 2023). Nevertheless, the growing dependence on AI-generated outputs has generated debates concerning authenticity, originality, and responsible use. Consequently, understanding the role of generative AI in English language education is essential to evaluating both its pedagogical potential and its ethical implications.

B. Ethical Issues in Generative Artificial Intelligence

The increasing use of generative AI has brought not only educational opportunities but also numerous ethical concerns. According to UNESCO's Recommendation on the Ethics of Artificial Intelligence (2021), AI technologies should be developed and implemented based on principles of transparency, accountability, fairness, privacy, and human autonomy. These principles are particularly relevant in educational contexts where learning outcomes and academic values are closely linked to students' intellectual development.

One major concern is academic integrity, as students may misuse AI-generated content for plagiarism or unauthorized assistance. Another issue is cognitive dependence, where excessive reliance on AI may reduce

learners' critical thinking and problem-solving abilities. Privacy and security also constitute significant concerns because AI platforms collect and process user data, raising questions regarding confidentiality and data protection. Moreover, algorithmic bias and fairness remain problematic since AI systems may reproduce stereotypes and cultural biases embedded in training datasets. Therefore, understanding these ethical dimensions is crucial for ensuring responsible and sustainable AI integration in language education.

C. Grand Theory: Critical Discourse Analysis by Norman Fairclough

Language as Social Practice

The theoretical foundation of this study is Critical Discourse Analysis (CDA) proposed by Norman Fairclough (1995, 2013). Fairclough argues that language is not merely a neutral medium for communication but a form of social practice through which meanings, ideologies, and power relations are produced and reproduced. In other words, discourse both reflects and shapes social realities.

From this perspective, ethical issues associated with generative AI are not viewed simply as individual opinions but as socially constructed phenomena influenced by cultural norms, educational values, and institutional practices. Students' perceptions regarding AI, therefore, are embedded within broader social and ideological contexts. CDA enables researchers to uncover the hidden assumptions and power structures underlying such perceptions.

Fairclough's Three-Dimensional Framework

Fairclough's model consists of three interconnected dimensions that allow researchers to analyze discourse comprehensively.

i) Text Analysis (Micro Level)

The first dimension focuses on the linguistic features of texts. It examines vocabulary choices, grammatical structures, modality, metaphors, and evaluative expressions. Through text analysis, researchers can identify how ethical concerns are represented linguistically and how certain meanings are emphasized or marginalized.

For example, students' statements such as "AI helps me complete assignments faster" or "I cannot write without ChatGPT" may reveal varying degrees of dependence, trust, or ethical awareness.

ii) Discursive Practice (Meso Level)

The second dimension concerns the processes through which discourse is produced, distributed, and consumed. Discursive practice examines how individuals create meanings, interact with texts, and interpret information.

In the context of generative AI, this dimension explores how students utilize AI-generated content, how they interact with AI systems, and how they perceive the boundaries between acceptable assistance and academic misconduct. It also investigates how educational institutions and digital platforms shape students' practices and attitudes toward AI use.

iii) Social Practice (Macro Level)

The third dimension investigates broader social and cultural structures that influence discourse. Social practice encompasses ideology, power relations, institutional norms, and socio-cultural contexts.

Within English language education, this dimension examines how academic culture, technological developments, and societal expectations contribute to students' understanding of ethical AI use. It also reveals how power relationships between human learners and AI technologies influence educational practices and decision-making processes.

Together, these three dimensions provide a comprehensive framework for understanding how ethical challenges associated with generative AI are constructed and negotiated among EFL students.

D. Supporting Theory: AI Ethics

Besides Critical Discourse Analysis, this study is supported by the theory of AI ethics, particularly UNESCO's Recommendation on the Ethics of Artificial Intelligence (2021). AI ethics refers to the principles and values that guide the responsible design, development, and use of artificial intelligence technologies. Its primary purpose is to ensure that AI benefits humanity while minimizing potential harms.

UNESCO proposes several ethical principles relevant to educational settings. Transparency requires AI systems to provide understandable and explainable outputs. Accountability emphasizes the responsibility of users, developers, and institutions for the consequences of AI-generated content. Fairness promotes equal opportunities and seeks to minimize discrimination and bias. Privacy and data protection safeguard users' personal information. Human agency and autonomy emphasize that AI should support rather than replace human decision-making and creativity.

These principles serve as a complementary framework for examining the ethical dimensions of generative AI use among EFL students. They also provide criteria for evaluating whether AI integration aligns with educational values and responsible practices.

E. Previous Studies (2021–2025)

The growing popularity of generative AI has attracted increasing scholarly attention in education and applied linguistics. Several recent studies have investigated both the opportunities and challenges associated with AI-assisted learning.

Kasneci *et al.* (2023), in *Learning and Individual Differences* (Scopus Q1), found that large language models provide significant benefits for education but simultaneously raise concerns regarding academic dishonesty and learner dependence. Similarly, Cotton *et al.* (2023) in *Innovations in Education and Teaching International* (Scopus Q1) emphasized that generative AI poses serious challenges to academic integrity and assessment practices.

Tlili *et al.* (2023), published in *Smart Learning Environments* (Scopus Q1), argued that ChatGPT presents

both opportunities and risks, requiring educators to balance innovation with ethical considerations. Meanwhile, Chan and Hu (2023) in *Education and Information Technologies* (Scopus Q1) reported that students expressed concerns regarding authenticity, fairness, and responsible AI use.

In higher education contexts, Ali *et al.* (2024) highlighted the importance of AI literacy and institutional governance to address ethical issues surrounding generative AI. In Indonesia, Yundayani *et al.* (2024), published in the *Journal on English as a Foreign Language* (SINTA 2), demonstrated that EFL students generally perceived ChatGPT positively in improving writing and language skills.

Although these studies provide valuable insights, most focus on perceptions, technology acceptance, and academic integrity. Few studies have explored how ethical concerns are discursively constructed and influenced by ideology and social practices. Moreover, research integrating mixed methods and Norman Fairclough's Critical Discourse Analysis remains scarce.

F. Research Gap

Based on the review of previous studies, several gaps can be identified. First, prior research has predominantly emphasized the benefits and acceptance of generative AI rather than its ethical dimensions. Second, most studies employ quantitative or phenomenological approaches, with limited use of critical perspectives. Third, little attention has been paid to how ethical concerns are socially and discursively constructed among EFL students. Finally, the integration of mixed methods and Fairclough's Critical Discourse Analysis in investigating AI ethics within English language education remains underexplored.

Therefore, this study seeks to address these gaps by employing an explanatory sequential mixed-methods design and Norman Fairclough's Critical Discourse Analysis framework to examine the ethical challenges of generative AI use among EFL students. By doing so, the study aims to provide a deeper understanding of the ideological, discursive, and socio-cultural factors underlying students' perceptions and practices regarding generative AI in English language education.

III. METHODOLOGY

A. Research Design

This study employs a mixed-methods approach using an explanatory sequential design proposed by Creswell and Plano Clark (2018). The explanatory sequential design consists of two phases in which quantitative data are collected and analyzed first, followed by qualitative data collection and analysis to explain and enrich the quantitative findings.

In the quantitative phase, questionnaire data are collected to identify the ethical challenges experienced by EFL students when using generative AI for English language learning. In the qualitative phase, semi-structured interviews are conducted to obtain a deeper understanding of students' experiences and perceptions regarding ethical issues associated with AI use. Finally, the findings from both

phases are integrated to provide a comprehensive understanding of the phenomenon under investigation.

B. Research Participants

The participants of this study are undergraduate EFL students who have experience using generative AI tools, such as ChatGPT, Gemini, and Copilot, for English language learning.

i) Quantitative Participants

For the quantitative phase, 100 undergraduate EFL students are selected using convenience sampling. This sampling technique allows the researcher to collect data efficiently from participants who meet the research criteria and are readily accessible.

ii) Qualitative Participants

For the qualitative phase, 10 students are selected from among the questionnaire respondents through purposive sampling. The participants are chosen based on their experience using generative AI and their willingness to provide detailed information regarding ethical issues encountered during AI-assisted language learning.

C. Research Instruments

i) Questionnaire

A questionnaire is used to collect quantitative data. The instrument employs a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

The questionnaire consists of four dimensions adapted from UNESCO's Recommendation on the Ethics of Artificial Intelligence (2021) and previous studies on AI ethics in education.

Table 1 Table of Variable and Indicators

Variables	Indicators
Academic Integrity	Originality, plagiarism, responsible use of AI
Dependence on AI	Reliance on AI, independent learning, critical thinking
Privacy and Security	Data privacy, confidentiality, awareness of information security
Ethical Awareness	Understanding of responsible AI use, accountability, fairness

The questionnaire aims to measure students' perceptions regarding the ethical challenges associated with the use of generative AI in English language education.

ii) Semi-Structured Interviews

Semi-structured interviews are conducted to obtain deeper insights into students' experiences and perceptions regarding ethical issues related to generative AI use.

Examples of interview questions include:

1. Why do you use generative AI in learning English?
2. What benefits do you obtain from using generative AI?
3. What ethical concerns have you encountered while using AI?
4. Do you think AI affects your originality and critical thinking?

5. How do you determine whether AI use is ethical or unethical?
6. What role do teachers or institutional policies play in guiding AI use?

D. Data Collection Procedures

Study is conducted through the following stages:

Step 1: Literature Review

Relevant literature concerning generative AI, AI ethics, and English language education is reviewed to establish the theoretical foundation and identify research gaps.

Step 2: Instrument Development

Questionnaire items and interview questions are developed based on UNESCO's ethical principles for artificial intelligence and previous studies.

Step 3: Questionnaire Distribution

The questionnaire is distributed to 100 undergraduate EFL students who have experience using generative AI for English language learning.

Step 4: Quantitative Data Analysis

The questionnaire responses are analyzed to identify the major ethical challenges perceived by students.

Step 5: Selection of Interview Participants

Ten participants are selected from among the survey respondents through purposive sampling.

Step 6: Conducting Interviews

Semi-structured interviews are conducted to obtain more detailed information regarding students' experiences and perceptions.

Step 7: Data Transcription

Interview recordings are transcribed verbatim to facilitate analysis.

Step 8: Qualitative Data Analysis

Interview transcripts are analyzed to identify themes related to ethical challenges associated with generative AI use.

Step 9: Integration of Findings

The findings from the quantitative and qualitative phases are integrated to provide a comprehensive understanding of the research problem.

Step 10: Drawing Conclusions

Conclusions and implications are formulated based on the integrated findings.

E. Data Analysis

i) Quantitative Data Analysis

Quantitative data obtained from the questionnaire are analyzed using the Statistical Package for the Social Sciences (SPSS).

The analysis includes:

- a. Frequency;
- b. Percentage;
- c. Mean;
- d. Standard deviation.

These descriptive statistics are used to describe students' perceptions regarding the ethical challenges of generative AI use in English language education.

ii) Qualitative Data Analysis

Qualitative data obtained from the interviews are analyzed using thematic analysis proposed by Braun and Clarke (2006).

The analysis consists of six stages:

1. Familiarizing with the data;
2. Generating initial codes;
3. Searching for themes;
4. Reviewing themes;
5. Defining and naming themes;
6. Producing the report.

The themes identified from the interviews are used to explain and support the quantitative findings.

F. Validity and Trustworthiness

i) Quantitative Validity

To ensure the quality of the questionnaire, the following procedures are employed:

- a. Content validity through expert judgment;
- b. Reliability testing using Cronbach's Alpha.

ii) Qualitative Trustworthiness

Following Lincoln and Guba (1985), the trustworthiness of qualitative findings is established through four criteria:

1. Credibility

Credibility is ensured through member checking, in which participants are given opportunities to verify the accuracy of the interview data and interpretations.

2. Transferability

Transferability is achieved by providing detailed descriptions of the research context and participants, allowing readers to determine the applicability of the findings to other settings.

3. Dependability

Dependability is maintained by documenting the research procedures systematically to ensure consistency throughout the study.

4. Confirmability

Confirmability is established by ensuring that the findings are derived from participants' experiences rather than researcher bias.

Furthermore, triangulation between questionnaire and interview findings is employed to enhance the trustworthiness of the study.

G. Ethical Considerations

Prior to data collection, participants are informed about the objectives and procedures of the study. Participation is voluntary, and informed consent is obtained from all participants. Participants are assured that their identities and personal information will remain confidential and that the collected data will be used solely for academic purposes. Participants also have the right to withdraw from the study at any stage without any consequences.

IV. RESULTS AND DISCUSSION

This section presents and discusses the findings of the study based on the three research questions. Following the explanatory sequential mixed-methods design, quantitative findings are presented first to identify the ethical challenges perceived by EFL students regarding the use of generative AI in English language education. The quantitative findings are subsequently elaborated through qualitative findings derived from semi-structured interviews and interpreted using Norman Fairclough's Critical Discourse Analysis (CDA) framework. The integration of quantitative and qualitative findings provides a comprehensive understanding of how ethical concerns are perceived, represented, and negotiated among EFL students in AI-assisted language learning environments.

A. Ethical Challenges Perceived by Efl Students

This section addresses the first research question: *What ethical challenges are perceived by EFL students regarding the use of generative AI in English language education?*

Data obtained from the questionnaire indicate that EFL students generally perceive generative AI as a beneficial learning tool. However, they also recognize several ethical challenges associated with its use. Four major ethical dimensions emerged from the quantitative findings, namely academic integrity, dependence on AI, privacy and security, and ethical awareness.

Table 2 Ethical Challenges of Generative AI Use among EFL Students

Ethical Dimension	Mean	SD	Interpretation
Academic Integrity	4.31	0.58	High
Dependence on AI	4.18	0.63	High
Privacy and Security	3.82	0.71	Moderate
Ethical Awareness	4.27	0.55	High

The findings reveal that academic integrity represents the most prominent ethical concern among participants. Many students acknowledged that generative AI may facilitate plagiarism and reduce originality if AI-generated content is submitted without modification or proper attribution. Students also expressed concern that AI-generated responses could be misused to complete assignments without adequate personal effort.

The second major challenge is dependence on AI. Participants reported frequent reliance on AI tools for grammar correction, essay writing, vocabulary development, and idea generation. While such assistance improves learning efficiency, students recognized the risk of becoming overly dependent on AI systems, potentially reducing their critical thinking and problem-solving abilities.

Privacy and security issues emerged as another ethical concern. Although students regularly use AI platforms, many admitted limited awareness regarding data collection practices, confidentiality, and information security. This finding suggests that students tend to focus on the functional benefits of AI while paying less attention to privacy-related implications.

The results also indicate a relatively high level of ethical awareness among participants. Students generally understood that responsible AI use requires accountability, verification of information, and adherence to academic integrity principles. Nevertheless, awareness alone does not necessarily prevent unethical practices, particularly when institutional guidelines regarding AI use remain unclear.

Overall, the quantitative findings demonstrate that EFL students perceive generative AI as both a valuable educational resource and a potential source of ethical challenges. These findings answer the first research question by identifying academic integrity, AI dependence, privacy concerns, and ethical awareness as the primary ethical issues associated with generative AI use in English language education.

B. Representation of Ethical Concerns in Students' Discourse

Despite its benefits, participants identified several challenges associated with the adoption of Generative AI. This section addresses the second research question: *How are ethical concerns represented in students' discourses concerning generative AI?*

To gain a deeper understanding of the quantitative findings, semi-structured interviews were conducted with ten selected participants. The thematic analysis revealed four dominant themes representing students' ethical concerns regarding generative AI use.

Theme 1: Academic Integrity and Originality

The majority of participants emphasized that generative AI should function as a supporting tool rather than a substitute for students' own work. Ethical concerns were frequently associated with plagiarism, originality, and academic honesty.

One participant explained:

"ChatGPT helps me generate ideas, but submitting the answer directly without revision would be unethical because it is not completely my own work."

Similarly, another participant stated:

"Students still need to think and write independently. AI should assist learning, not replace it."

These statements suggest that students associate ethical AI use with maintaining originality and personal contribution in academic tasks.

Theme 2: Dependence and Reduced Critical Thinking

Another recurring theme concerns excessive reliance on AI technologies. Participants acknowledged that AI simplifies learning processes but may also reduce opportunities for independent thinking.

One participant commented:

"Sometimes I ask ChatGPT before trying to solve the problem myself."

Another participant noted:

"AI makes learning easier, but students may become less creative if they always depend on it."

These findings indicate that students perceive dependence on AI as a potential threat to critical thinking, creativity, and autonomous learning.

Theme 3: Privacy and Data Protection

Privacy concerns appeared less prominent compared to academic integrity issues. Nevertheless, several participants expressed uncertainty regarding how AI platforms manage user information.

One participant stated:

"I know AI stores information, but I do not really understand how the data are used."

Another participant admitted:

"I usually accept the privacy policy without reading it."

The findings suggest that although students recognize privacy issues, their understanding of data protection remains relatively limited.

Theme 4: Accountability and Responsible AI Use

The final theme relates to accountability and responsible technology use. Participants consistently emphasized the importance of verifying AI-generated information and maintaining responsibility for academic outputs.

One participant explained:

"Even when using AI, students should verify information because AI can sometimes provide incorrect answers."

Another participant stated:

"Users remain responsible for whatever they submit, even if the content was generated by AI."

These statements indicate that students perceive ethical AI use as a matter of personal responsibility, critical evaluation, and informed decision-making.

Overall, students' discourse represents ethical concerns through narratives of academic honesty, independent learning, privacy awareness, and accountability. These findings answer the second research question by demonstrating how ethical issues are constructed and articulated by EFL students within their educational experiences.

C. Discursive Practices Shaping Students' Attitudes toward Generative AI

This section addresses the third research question: *How do discursive practices shape EFL students' attitudes toward generative AI?*

To answer this question, interview data were further analyzed using Norman Fairclough's three-dimensional Critical Discourse Analysis framework consisting of text analysis, discursive practice, and social practice.

Text Analysis (Micro Level)

At the textual level, students frequently used positive expressions such as "helpful," "efficient," "practical," and "time-saving" when describing generative AI. These lexical choices construct AI as a beneficial educational technology that supports language learning and academic performance. However, participants also employed negative expressions such as "dependence," "plagiarism," "lazy thinking," and "misuse." Such language reflects concerns regarding the ethical consequences of excessive AI use.

The coexistence of positive and negative vocabulary demonstrates that students simultaneously perceive AI as both an educational opportunity and an ethical challenge. This dual representation reflects an ambivalent discourse surrounding generative AI in English language education.

Discursive Practice (Meso Level)

At the level of discursive practice, students actively interact with, interpret, and reproduce AI-generated content. Most participants reported using AI for grammar correction, writing support, vocabulary enhancement, translation, and brainstorming activities.

The findings indicate that students continuously negotiate the boundaries between acceptable and unacceptable AI use. AI-assisted learning is generally considered ethical when used to support understanding and improve language skills. In contrast, direct submission of AI-generated content without revision is viewed as unethical and inconsistent with academic values.

Therefore, students' attitudes toward AI are shaped through their everyday interactions with AI technologies and their interpretations of appropriate educational practices.

Social Practice (Macro Level)

At the broader social level, students' attitudes toward generative AI are influenced by technological developments, educational expectations, and institutional norms. The rapid digitalization of higher education has normalized AI use as part of contemporary learning practices.

At the same time, traditional academic values emphasizing originality, critical thinking, and independent learning continue to influence students' ethical judgments. As a result, students often experience tension between the desire for efficiency and the expectation to maintain academic integrity.

From Fairclough's perspective, these findings suggest that ethical understandings of generative AI are socially constructed through interactions among technological innovation, educational culture, and institutional

expectations. Students' attitudes are therefore shaped not only by personal experiences but also by broader social and ideological influences.

D. Discussion

The findings reveal that EFL students recognize both the benefits and ethical challenges associated with generative AI use in English language education. Academic integrity emerged as the most significant ethical concern, followed by dependence on AI, privacy issues, and responsible use. These findings support previous studies suggesting that while generative AI enhances learning efficiency and language development, it also raises concerns regarding plagiarism, learner autonomy, and academic honesty.

The qualitative findings further demonstrate that ethical concerns are represented through discourses of originality, accountability, critical thinking, and responsible technology use. Students generally view AI as an educational assistant rather than a replacement for human effort. Nevertheless, the increasing reliance on AI technologies may create challenges for maintaining independent learning and authentic academic performance.

The Critical Discourse Analysis reveals that students' attitudes toward generative AI are shaped by multiple layers of discourse. At the textual level, AI is represented as both beneficial and potentially problematic. At the discursive practice level, students negotiate ethical boundaries through everyday interactions with AI-generated content. At the social practice level, broader educational values and technological developments influence how ethical AI use is understood and enacted.

Overall, the findings indicate that responsible AI integration in English language education requires not only technological literacy but also ethical literacy. Educational institutions should therefore develop clear guidelines and policies that encourage students to utilize generative AI responsibly while maintaining academic integrity, critical thinking, and learner autonomy.

IV. CONCLUSION

This study investigated the ethical challenges of generative AI use among EFL students and explored how these issues are represented and constructed within students' discourse. Based on the findings, several conclusions can be drawn.

First, EFL students perceive generative AI as a highly useful learning tool, particularly for writing support, grammar correction, idea generation, and vocabulary development. However, despite these benefits, students also recognize significant ethical challenges in its use. The most prominent concern is academic integrity, followed by dependence on AI, ethical awareness, and privacy and security issues.

Second, from the perspective of Critical Discourse Analysis (Fairclough, 1995, 2013), ethical concerns are constructed through students' language and everyday learning practices. Students represent generative AI in a dual way: as both a helpful educational assistant and a potential source of academic misconduct. This ambivalence reflects

their ongoing negotiation of ethical boundaries in AI-assisted learning environments.

Third, students' attitudes toward generative AI are shaped by three interconnected levels of discourse. At the textual level, AI is described using both positive and negative terms such as "helpful" and "time-saving" as well as "dependence" and "misuse." At the discursive practice level, students actively interpret and regulate their use of AI depending on academic tasks. At the social practice level, institutional expectations, academic norms, and rapid technological development influence how ethical AI use is understood.

Overall, the findings indicate that while generative AI enhances learning efficiency for EFL students, it also raises important ethical concerns that require attention. Therefore, generative AI should be viewed as a supporting learning tool rather than a replacement for human effort and academic responsibility.

REFERENCES

- [1] Ali, M., Aboelmaged, M., & Mouakket, S. (2024). Artificial intelligence literacy and ethical considerations in higher education: Challenges and future directions. *Education Sciences*, 14(2), 154. <https://doi.org/10.3390/educsci14020154>
- [2] Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77–101. <https://doi.org/10.1191/1478088706qp063oa>
- [3] Chan, C. K. Y., & Hu, W. (2023). Students' voices on generative AI: Perceptions, benefits, and ethical concerns. *Education and Information Technologies*, 29, 8217–8245.
- [4] Chan, C. K. Y., & Zhou, W. (2023). Deconstructing student perceptions of generative AI through an expectancy-value theory-based instrument. *Computers and Education: Artificial Intelligence*, 4, 100134. <https://doi.org/10.1016/j.caeai.2023.100134>
- [5] Cotton, D. R. E., Cotton, P. A., & Shipway, J. R. (2023). Chatting and cheating? Ensuring academic integrity in the era of ChatGPT. *Innovations in Education and Teaching International*, 61(2), 228–239. <https://doi.org/10.1080/14703297.2023.2190148>
- [6] Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). Sage Publications.
- [7] Fairclough, N. (1995). *Critical discourse analysis: The critical study of language*. Longman.
- [8] Fairclough, N. (2013). *Critical discourse analysis: The critical study of language* (2nd ed.). Routledge.
- [9] Halim, A. (2026). A critical multi-case study of generative AI in GELT: Representing diverse Englishes and ethical-psychological challenges. *JEELS (Journal of English Education and Linguistics Studies)*, 13(1), 267–294. <https://doi.org/10.30762/jeels.v13i1.7728>
- [10] Kasneci, E., Sessler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., Gasser, U., Groh, G., Günemann, S., Hüllermeier, E., Krusche, S., Kutyniok, G., Michaeli, T., Nerdel, C., Pfeiffer, F., Poquet, O., Sailer, M., Schmidt, A., Seidel, T., & Kasneci, G. (2023). ChatGPT for good? On opportunities and challenges of large language models for education. *Learning and Individual Differences*, 103, 102274. <https://doi.org/10.1016/j.lindif.2023.102274>
- [11] Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Sage Publications.
- [12] Matthews, B., & Peer Mohamed, M. S. (2025). Generative AI, ethics, and language learning. In L. McCallum & D. Tafazoli (Eds.), *The Palgrave encyclopedia of computer-assisted language learning*. Palgrave Macmillan. https://doi.org/10.1007/978-3-031-51447-0_94-2
- [13] Rashid, S., Malik, S., & Ghauri, F. (2026). The Active Learning–GenAI Synergy Framework: Ethical integration of generative AI in EFL/ESL writing in resource-constrained contexts. *F1000Research*, 14, 1210. <https://doi.org/10.12688/f1000research.171435.2>
- [14] Sharples, M. (2023). Towards social generative AI for education: Theory, practices and ethics. In *Lecture Notes in Educational Technology* (pp. 277–287). Springer. https://doi.org/10.1007/978-981-99-2060-1_19
- [15] Tlili, A., Shehata, B., Adarkwah, M. A., Bozkurt, A., Hickey, D. T., Huang, R., & Agyemang, B. (2023). What if the devil is my guardian angel? ChatGPT as a case study of using chatbots in education. *Smart Learning Environments*, 10(1), 15. <https://doi.org/10.1186/s40561-023-00237-x>
- [16] UNESCO. (2021). *Recommendation on the ethics of artificial intelligence*. UNESCO Publishing.
- [17] Wang, X., & Zhang, L. (2024). Improving EFL students' cultural awareness: Reframing moral dilemmatic stories with ChatGPT. *Computers and Education: Artificial Intelligence*, 6, 100223. <https://doi.org/10.1016/j.caeai.2024.100223>
- [18] Williams, R. T. (2024). The ethical implications of using generative chatbots in higher education. *Frontiers in Education*, 8, Article 1331607. <https://doi.org/10.3389/feduc.2023.1331607>
- [19] Yundayani, A., Emzir, & Rafli, Z. (2024). Students' perceptions of ChatGPT in English language learning. *Journal on English as a Foreign Language*, 14(1), 1–22.

Digital Literacy as a Key Competency for 21st-Century Learners in Elementary Education

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ABSTRACT — Digital literacy has become an essential competency for learners in the twenty-first century due to the rapid advancement of digital technologies and their increasing integration into education. This study aims to examine the role of digital literacy as a key competency for elementary school students and explore its significance in supporting twenty-first-century learning. Using a literature review approach, this paper analyzes and synthesizes findings from previous studies, policy documents, and theoretical frameworks related to digital literacy in elementary education. The review highlights that digital literacy extends beyond technical skills and includes information evaluation, communication, critical thinking, collaboration, and responsible digital citizenship. The findings also indicate that the development of digital literacy in elementary schools is influenced by factors such as technological infrastructure, teacher readiness, curriculum integration, and access to digital resources. Despite various implementation challenges, effective digital literacy programs can support students in becoming competent, critical, and responsible users of technology. This study concludes that strengthening digital literacy in elementary education is essential for preparing learners to participate successfully in an increasingly digital society and to meet the demands of twenty-first-century learning.

KEYWORDS: Digital literacy, elementary education, 21st-century skills, digital competence, digital citizenship.

I. INTRODUCTION

The rapid advancement of digital technology has transformed various aspects of human life, including communication, information access, learning, and problem-solving activities [1]. In the twenty-first century, students are expected not only to master traditional literacy skills but also to develop competencies that enable them to participate effectively in increasingly digital environments. As a result, digital literacy has emerged as one of the most important competencies required for lifelong learning, academic success, and active participation in society [2].

Digital literacy refers to the ability to access, evaluate, create, and communicate information using digital technologies in a responsible and effective manner [2]. It extends beyond the technical operation of digital devices and includes critical thinking, information evaluation, digital communication, and ethical technology use. Consequently, digital literacy has become a fundamental component of twenty-first-century education, supporting students' ability

to adapt to technological changes and engage in meaningful learning experiences [3].

At the elementary school level, digital literacy plays a particularly important role because children are increasingly exposed to digital technologies from an early age. Students interact with smartphones, computers, educational applications, and online resources both inside and outside the classroom. Therefore, schools have a responsibility to provide learning experiences that help students develop the knowledge, skills, and attitudes necessary for responsible digital participation and lifelong learning [4].

Despite its importance, the implementation of digital literacy in elementary education continues to face several challenges. Previous studies have identified limited technological infrastructure, insufficient teacher preparedness, and a lack of developmentally appropriate learning resources as major barriers to effective digital literacy integration [3], [4]. In many cases, digital literacy instruction remains focused on basic technology use rather than fostering higher-order competencies such as critical evaluation of information, digital collaboration, and responsible online behavior.

In Indonesia, efforts to strengthen digital literacy have gained increasing attention in recent years. However, variations in school readiness, teacher competence, and access to technology continue to influence the quality of digital literacy implementation in elementary schools [2], [4]. These challenges indicate the need for more comprehensive approaches that support the development of digital literacy as a core competency for young learners.

Therefore, this study aims to explore the development of digital literacy as a key competency for twenty-first-century learners in elementary education. The findings are expected to provide valuable insights for educators, curriculum developers, and policymakers in designing learning environments that equip students with the skills necessary to thrive in an increasingly digital society.

II. LITERATURE REVIEW

A. Digital Literacy

Digital literacy refers to the ability to effectively access, evaluate, create, and communicate information through digital technologies [5]. The concept extends beyond technical skills in operating digital devices and includes critical thinking, information management, online communication, and responsible digital citizenship. In contemporary education, digital literacy is considered an essential competency that enables learners to navigate digital environments safely, ethically, and productively [6].

The growing availability of digital technologies has significantly increased the need for digital literacy among students. Learners are constantly exposed to online information, digital platforms, and social media, making it necessary for them to develop the ability to distinguish reliable information from misinformation and use technology responsibly [7]. Therefore, digital literacy has become an integral component of educational systems worldwide.

B. Digital Literacy as a 21st-Century Competency

Twenty-first-century education emphasizes the development of competencies that prepare learners for the challenges of a rapidly changing world. These competencies commonly include critical thinking, creativity, communication, collaboration, and digital literacy [8]. Among these skills, digital literacy serves as a foundational competency because it supports students in accessing knowledge, solving problems, and participating in digital learning environments.

Researchers have highlighted that digital literacy contributes to academic achievement and lifelong learning by enabling students to effectively utilize digital resources and technologies [9]. Furthermore, digitally literate learners are better prepared to adapt to technological advancements, engage in innovative practices, and participate actively in the digital economy. Consequently, many educational policies worldwide have integrated digital literacy into curriculum frameworks to ensure that students are equipped with the competencies required for future success [10].

C. Digital Literacy in Elementary Education

Elementary education represents a critical stage for developing digital literacy because students begin to interact more frequently with digital technologies both inside and outside the classroom [11]. Early exposure to digital literacy can help children develop responsible technology-use habits, critical evaluation skills, and positive attitudes toward learning with technology.

However, implementing digital literacy at the elementary level presents several challenges. Teachers often face limitations related to technological infrastructure, instructional resources, and professional development opportunities [12]. Additionally, digital literacy instruction must be adapted to the cognitive and developmental characteristics of young learners to ensure meaningful learning experiences. Therefore, effective digital literacy programs should incorporate age-appropriate activities,

interactive learning environments, and opportunities for students to apply digital skills in authentic contexts [13].

Given the increasing importance of digital literacy in modern education, strengthening digital literacy development in elementary schools is essential for preparing students to become competent and responsible participants in the digital society. This perspective forms the foundation for examining digital literacy as a key competency for twenty-first-century learners.

III. DISCUSSION

A. The Importance of Digital Literacy for 21st-Century Learners

Digital literacy has become an essential competency for learners in the twenty-first century. The increasing integration of digital technologies into education, communication, and daily life requires students to possess skills that enable them to access, evaluate, and utilize digital information effectively. Digital literacy supports the development of critical thinking, problem-solving, communication, and collaboration skills, which are widely recognized as core competencies for success in modern society [8], [9].

Furthermore, digitally literate students are better prepared to participate in technology-rich learning environments and adapt to continuous technological changes. Studies have shown that digital competence is closely associated with students' ability to engage in lifelong learning and knowledge creation in digital environments [14], [15].

B. Challenges in Developing Digital Literacy in Elementary Schools

Despite its importance, developing digital literacy among elementary school students remains a significant challenge. One of the primary barriers is the unequal availability of technological infrastructure across schools. Many educational institutions, particularly in developing regions, continue to experience limited access to digital devices, internet connectivity, and technology-based learning resources.

Teacher readiness also plays a crucial role in the successful implementation of digital literacy education. Previous studies have reported that many teachers lack sufficient training and confidence in integrating digital technologies into classroom instruction. As a result, digital literacy activities are often limited to basic technology use rather than fostering higher-order skills such as information evaluation, digital communication, and ethical online behavior.

Another challenge relates to the developmental characteristics of young learners. Elementary school students require age-appropriate learning experiences that are engaging, interactive, and aligned with their cognitive abilities. Consequently, digital literacy programs must be carefully designed to ensure that students can develop digital competencies in meaningful and developmentally appropriate ways.

C. Strategies for Strengthening Digital Literacy in Elementary Education

To effectively develop digital literacy among elementary school students, several strategies should be considered. First, schools need to provide supportive learning environments that encourage students to use digital technologies responsibly and productively. This includes access to appropriate digital resources and opportunities for hands-on learning experiences.

Second, continuous professional development should be provided for teachers to enhance their digital competence and instructional capabilities. Well-prepared teachers are more likely to integrate digital literacy effectively into classroom practices and create meaningful learning experiences for students.

Third, digital literacy should be integrated across different subject areas rather than being taught as a separate topic. Cross-curricular integration enables students to apply digital skills in various learning contexts, thereby strengthening their understanding and practical application of digital literacy competencies [10], [15].

Finally, collaboration among schools, families, and communities is essential for supporting students' digital literacy development. Parents and community stakeholders can contribute by promoting responsible technology use and providing additional opportunities for students to practice digital skills beyond the classroom.

Overall, the literature indicates that digital literacy is a critical competency for twenty-first-century learners. Although various challenges remain, strategic efforts involving educators, schools, families, and policymakers can significantly enhance digital literacy development in elementary education and prepare students for successful participation in an increasingly digital society.

IV. CONCLUSION

Digital literacy has become one of the most essential competencies for twenty-first-century learners, particularly in the context of rapid technological advancement and increasing digitalization in education. The literature reviewed in this study indicates that digital literacy extends beyond technical skills and encompasses critical thinking, information evaluation, communication, collaboration, and responsible digital citizenship. These competencies are crucial for preparing students to participate effectively in modern society and lifelong learning environments.

At the elementary education level, digital literacy should be introduced through developmentally appropriate learning experiences that support students' cognitive, social, and technological growth. However, several challenges continue to hinder its implementation, including limited technological infrastructure, insufficient teacher preparedness, and unequal access to digital resources. To address these challenges, schools should strengthen teacher professional development, integrate digital literacy across the curriculum, and promote collaboration among educators, families, and communities.

Overall, developing digital literacy in elementary education is essential for preparing students to become competent, critical, and responsible users of technology. Future studies are encouraged to explore effective instructional strategies and innovative learning models that can further enhance digital literacy development among young learners.

REFERENCES

- [1] K. S. Gita and M. I. P. Nasution, "Perkembangan Teknologi Informasi di Indonesia: Tantangan dan Peluang," *Jurnal Sains Student Research*, vol. 3, no. 1, pp. 21–33, 2025.
- [2] R. Fajriati, M. Suri, and A. Qadrunnada, "Digital Literacy in Learning at State Elementary School in Banda Aceh," *Journal of Education Science (JES)*, vol. 11, no. 1, pp. 57–60, 2025.
- [3] I. Hartati, H. Susanah, and S. Iskandar, "Integration of Digital Skills in Elementary School Learning: Facing Challenges in the 21st Century," *Inovasi Sekolah Dasar: Jurnal Kajian Pengembangan Pendidikan*, vol. 12, no. 1, pp. 313–323, 2025.
- [4] N. N. Padmadewi, L. P. Artini, N. M. Ratminingsih, and I. K. A. Ana, "Elementary School Teachers' Readiness in Teaching Technology-Based Literacy," *International Journal of Elementary Education*, vol. 7, no. 2, pp. 299–310, 2023.
- [5] P. Gilster, *Digital Literacy*. New York, NY, USA: Wiley Computer Publishing, 1997.
- [6] D. Belshaw, *The Essential Elements of Digital Literacies*. Durham, U.K.: Durham University, 2014.
- [7] Y. Eshet-Alkalai, "Digital Literacy: A Conceptual Framework for Survival Skills in the Digital Era," *Journal of Educational Multimedia and Hypermedia*, vol. 13, no. 1, pp. 93–106, 2004.
- [8] P. Griffin, B. McGaw, and E. Care, *Assessment and Teaching of 21st Century Skills*. Dordrecht, Netherlands: Springer, 2012.
- [9] J. Fraillon, J. Ainley, W. Schulz, T. Friedman, and E. Duckworth, *Preparing for Life in a Digital World: IEA International Computer and Information Literacy Study 2018 International Report*. Cham, Switzerland: Springer, 2020.
- [10] UNESCO, *Global Framework of Reference on Digital Literacy Skills for Indicator 4.4.2*. Paris, France: UNESCO Institute for Statistics, 2018.
- [11] M. Ribble, *Digital Citizenship in Schools*, 3rd ed. Eugene, OR, USA: International Society for Technology in Education (ISTE), 2015.
- [12] C. Redecker, *European Framework for the Digital Competence of Educators (DigCompEdu)*. Luxembourg: Publications Office of the European Union, 2017.
- [13] N. N. Padmadewi, L. P. Artini, and N. M. Ratminingsih, "Technology-Based Literacy and Elementary Education in the Digital Era," *International Journal of Elementary Education*, 2023.
- [14] O. E. Hatlevik, M. Guðmundsdóttir, and J. Loi, "Digital Diversity Among Upper Secondary Students: A Multilevel Analysis of the Relationship Between Cultural Capital, Self-Efficacy, Strategic Use of Information and Digital Competence," *Computers & Education*, vol. 81, pp. 345–353, 2015.
- [15] UNESCO, *Digital Literacy in Education and Lifelong Learning*. Paris, France: UNESCO Publishing, 2023.

The Role of ChatGPT in Enhancing Scientific English Writing Skills Among Health Science Students

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ABSTRACT — ChatGPT is a large language model-based artificial intelligence model designed to process, understand, and generate natural language text contextually, so that it can be used in various academic activities, including scientific writing. These technological developments have made an important contribution to the improvement of scientific English writing skills in health science students in college. The ability to write in English is an important competency required in the preparation of academic assignments, scientific publications, and academic communication. This study aims to analyze the role of ChatGPT in supporting the improvement of scientific English writing skills of health science students based on the aspects of analyzing, evaluating, and creating, as well as reviewing from the frequency of use, duration of use, and purpose of use. This study uses a descriptive quantitative approach with a survey method. Data were collected through questionnaires and analyzed using descriptive statistics in the form of frequency (n) and percentage (%), as well as score analysis based on the Likert scale. The results showed that the indicators created obtained the highest score (75.93%), followed by analyzing (72.38%) and evaluating (71.58%). Most college students use ChatGPT 2–3 times per week, and the majority have been using it for more than a year. Based on the purpose of use, ChatGPT is most widely used to compile academic assignments, followed by article translation and scientific reference search. ChatGPT has proven to play a significant role in supporting the improvement of scientific English writing skills of health science students, especially in assisting with the preparation of academic texts, the development of ideas, translation, and language improvement. These findings show that ChatGPT not only serves as a technical tool, but also as a facilitator in the development of students' high-level thinking skills.

KEYWORDS: AI in education, ChatGPT, critical thinking, health science, scientific writing.

I. INTRODUCTION

The ability to write scientific English is an important skill that health science students need to have, as it supports academic communication and the application of *evidence-based practice* at the global level. In the health field, access to international literature is of paramount importance as

most clinical guidelines, research results, and scientific publications are written in English. Therefore, the ability to understand and produce good scientific writing not only affects the academic success of students, but also relates to the readiness of students to improve the quality of health services in the future [1].

Throughout the learning process, writing skills play a considerable role in various health-related courses, particularly nursing courses such as medical-surgical nursing, community nursing, critical care nursing, and research methodology. Students are required to not only read international journals, but also compile nursing reports and write assignments based on scientific articles [2]. However, in practice, there are still many students who have difficulties when they have to write in English, especially in composing the right sentences, connecting paragraphs coherently, and developing ideas systematically [3]. These difficulties are generally related to limited mastery of academic vocabulary, lack of confidence in writing, and lack of experience in compiling ideas scientifically. This has an impact on student writing results that are not optimal and do not fully meet the expected international scientific writing standards [4] [5].

The development of digital technology in recent years has brought major changes in the world of education, including the presence of artificial intelligence (AI). One of the most widely used technologies today is ChatGPT, which is a *large language model* designed to understand and generate natural language-based text. In the context of nursing learning, ChatGPT is beginning to be used as an academic writing tool, for example to help formulate ideas, improve sentence structure, provide alternative academic expressions, and support the development of paragraphs to be more directed. Previous research has shown that ChatGPT has the potential to help the academic writing process, especially in the development of writing ideas and structures [6] [7].

ChatGPT technology is also widely used to support *writing assistance activities*, such as translation, paraphrasing, and grammar improvement [8]. Other studies have also suggested that *generative AI* can help increase students' academic productivity while supporting a more independent and effective writing-based learning process [9]. However, the use of ChatGPT in nursing education is also inseparable from various challenges. ChatGPT can help improve learning efficiency and writing quality, but on the other hand, there are concerns related to reliance on AI, decreased critical thinking skills, and academic integrity issues [10].

Therefore, it is important to understand how ChatGPT is actually used by nursing students in the learning process, particularly in the development of scientific writing skills. Based on this, this study aims to analyze the role of ChatGPT in improving *the scientific English writing skills* of health science students, especially nursing, based on the ability to analyze, evaluate, and create, as well as review from the frequency of use, duration of use, and purpose of use of ChatGPT.

II. METHODOLOGY

A. Research Design

This study uses a quantitative approach with a descriptive survey design to obtain an overview of students' perceptions of the role of ChatGPT in improving scientific writing skills in English. The survey approach was chosen because it was able to systematically collect information about respondents' views and experiences on the use of artificial intelligence technology in the learning process [11]. The research is focused on the use of ChatGPT as a supporting medium in the preparation of scientific and academic writings for nursing students who are taking Basic Nursing courses in the even semester of the 2025/2026 Academic Year.

B. Research Participants

The participants in this study were 80 second-semester nursing students enrolled in the Basic Nursing course during the Even Semester of the 2025/2026 Academic Year at Universitas Haji Sumatera Utara. A total population sampling approach was employed, allowing all students from the two classes to participate in the study. Although the corresponding author's primary affiliation is Universitas Deztron Indonesia, the author is also engaged in teaching activities within the Nursing Study Program at Universitas Haji Sumatera Utara, which facilitated access to the participants. Before data collection, all students were informed of the study objectives and provided their voluntary consent to participate.

C. Research Instrument

The research instrument is in the form of a closed questionnaire that was compiled to measure students' perceptions of the role of ChatGPT in improving academic skills and scientific writing in English. The questionnaire consists of 12 statements developed based on three indicators of *higher order thinking skills* (Table 1) [12].

Table 1 Questionnaire Indicators in Thinking Ability

Indicator	Item Number	Number of Items
Analyzing	1, 2, 3, 4	4
Evaluating	5, 6, 7, 8	4
Creating	9, 10, 11, 12	4
Total	1–12	12

Each statement is prepared to describe students' perceptions of ChatGPT's contribution in understanding scientific literature, evaluating the quality of writing, and developing ideas into systematic academic writing [13].

D. Data Collection Procedure

Data were collected by administering questionnaires to all nursing students enrolled in the Basic Nursing course after they had utilized ChatGPT as a supporting tool for completing academic writing tasks. Before data collection, respondents were informed of the study objectives and the procedures for completing the questionnaire. Participation was voluntary, and all responses were kept confidential and used exclusively for research purposes.

A total of 80 questionnaires were distributed to the participants, and all questionnaires were returned and included in the final analysis.

E. Data Analysis

The data were analyzed using descriptive methods by calculating the frequency, score, and percentage (%) of respondents' responses to each statement item. Instruments using a *five-level Likert scale* (Table 2).

Table 2 Five-Level Likert Scale

Components	Weight
Strongly Disagree (SD)	1
Disagree (D)	2
Neutral (N)	3
Agree (A)	4
Strongly Agree (SA)	5

The score of each item is obtained by adding up the multiplication between the frequency of the respondent's answers and the weight of the *Likert scale*. Furthermore, the percentage (%) is calculated using the formula:

$$P = \left(\frac{f}{N} \right) \times 100$$

Where f represents the frequency of responses and N represents the total number of respondents.

III. RESULTS AND DISCUSSION

The results show that students' perception of the role of ChatGPT in supporting scientific writing skills in English can be reviewed through three main indicators, namely the ability to analyze, evaluate, and create. These three indicators are important components of high-level thinking skills that play a role in the process of preparing scientific

papers, especially in the field of health sciences that require accurate information, critical thinking skills, and systematic delivery of ideas (Table 3).

Based on Table 3, most respondents gave a positive assessment of the use of ChatGPT as a supporting medium in the academic writing process. Students assessed that the use of ChatGPT helped them in understanding information from various English-language scientific sources, studying the quality of the written writing, and developing ideas into more structured and coherent scientific manuscripts. These findings indicate that ChatGPT is not only used as a means to obtain information, but also serves as a tool that supports the learning process through strengthening the ability to analyze, evaluate, and develop ideas.

The results show that the integration of ChatGPT in academic activities has the potential to make a positive contribution to improving the scientific writing skills of nursing students. The presence of artificial intelligence-based technology can be an alternative learning media that helps students in compiling academic writing that is more systematic, logical, and in accordance with the rules of scientific writing in English, as long as its use is accompanied by the ability to think critically and independently evaluate the information produced.

Table 3 Results of Nursing Students' Perception Based on the Five-Level Likert Scale

No	Indicator	Representation	SA	A	N	D	SD	Score	Percent (%)
1	Analyze	The use of ChatGPT helps to understand the structure of English scientific writing	4	38	34	2	2	280	70
2	Analyze	The use of ChatGPT makes it easier to identify main ideas from scientific references.	14	42	20	2	2	304	76
3	Analyze	The use of ChatGPT helps analyze information before it is written	12	30	34	0	4	286	71.5
4	Analyze	The use of ChatGPT supports the construction of logical arguments	12	32	30	4	2	288	72
5	Evaluate	The use of ChatGPT helps evaluate the quality of writing	4	26	34	14	2	256	64
6	Evaluate	The use of ChatGPT helps identify grammatical errors	12	37	24	6	1	293	73.3
7	Evaluate	The use of ChatGPT helps evaluate academic vocabulary	18	28	31	2	1	300	75
8	Evaluate	ChatGPT input improves the quality of scientific writing	9	44	23	2	2	296	74
9	Create	The use of ChatGPT helps develop ideas into academic paragraphs	12	50	14	2	2	308	77
10	Create	The use of ChatGPT makes it easier to create a written outline	10	52	17	0	1	310	77.5
11	Create	The use of ChatGPT supports more systematic writing	8	42	24	4	2	290	72.5
12	Create	The use of ChatGPT encourages the development of creative ideas	8	54	16	1	1	307	76.7

A. Analyze Indicators

The analysis indicator consists of four statements with consecutive percentages of 70%, 76%, 71.5%, and 72%. The average percentage of indicators analyzed was 72.38% (Figure 1). This score shows that health students have a good perception of the role of ChatGPT in helping the process of analyzing scientific writing in English. The statement with the highest score was "*The use of ChatGPT makes it easier to identify the main idea from scientific references*" (76%) (Table 3). These findings show that students are using ChatGPT to understand the content of academic reading and find key ideas from reference sources more quickly.

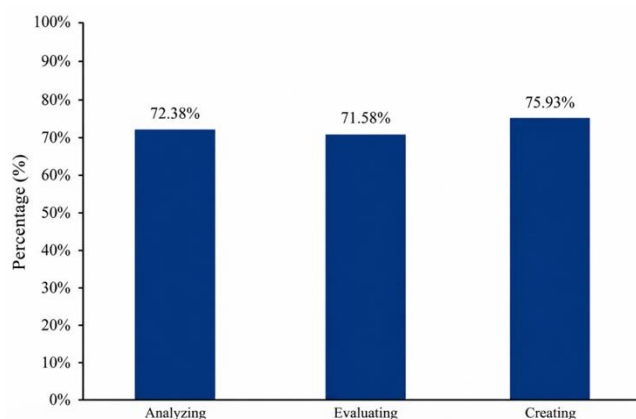


Figure 1. Comparison of students' perceptions across indicators.

Table 3, students also assessed that ChatGPT helps understand the structure of scientific writing (70%), analyze information before writing (71.5%), and compose logical arguments (72%). These results show that ChatGPT acts as a cognitive tool in the analysis stage before the writing process is carried out. These results are in line with research by Mahapatra [14] who found that the use of ChatGPT as a formative feedback tool helps students improve their ability to understand texts, develop ideas, and improve the quality of academic writing. Boudouaia *et al.* [15] show that EFL students view ChatGPT as an effective tool to help understand material, generate ideas, and complete academic writing assignments. In addition, research by Zhao *et al.* [16] suggests that generative AI has changed the writing process of students by providing support at the stage of idea exploration, information analysis, and concept development before writing is done.

B. Evaluating Indicators

The average percentage of indicators is 71.58% (Figure 1). These results show that students have a positive perception of ChatGPT's ability to help evaluate the quality of academic writing. The statement with the highest score was *"The use of ChatGPT helps evaluate academic vocabulary"* (75%), followed by *"ChatGPT input improves the quality of scientific writing"* (74%) (Table 3). Research shows that college students use ChatGPT to review grammar, academic word choice, and overall writing quality. ChatGPT serves as an evaluation tool that provides quick feedback on student writing results. These findings are in line with the research of Li *et al.* [17], who stated that ChatGPT is able to provide relevant assessments and feedback to EFL students' writing, especially in aspects of writing organization, grammar, and argument quality. Polakova and Ivens [18] shows that the feedback provided by ChatGPT contributes to improving students' writing skills, especially in language revision, sentence structure, and accuracy in the use of academic vocabulary. Researchers who compared human feedback and ChatGPT found that although lecturers still excelled overall, ChatGPT was quite effective in evaluating reasoning, argumentation, and the use of evidence in student writing.

C. Creating Indicators

The average percentage (Figure 1) of the indicator creates is 75.93%. This value is the highest compared to the two indicators analyzed and evaluated. These results show that students are very helpful in the process of creating or developing academic writing using ChatGPT. The statement with the highest score results was *"The use of ChatGPT facilitates the preparation of writing frameworks"* (77.5%), followed by *"The use of ChatGPT helps develop ideas into academic paragraphs"* (77%) (Table 3). This shows that students use ChatGPT more at the stage of developing ideas and preparing an initial draft of the writing. These results are in line with Mahapatra's [14] research which shows that students use ChatGPT to generate ideas, develop paragraphs, and increase creativity in academic writing. Bašić *et al.* [19] also show that ChatGPT helps students draft essays and speed up the writing process by providing examples of structure and development of writing content. Students consider ChatGPT to be an effective tool for

brainstorming, developing new ideas, and drafting more structured academic texts [15].

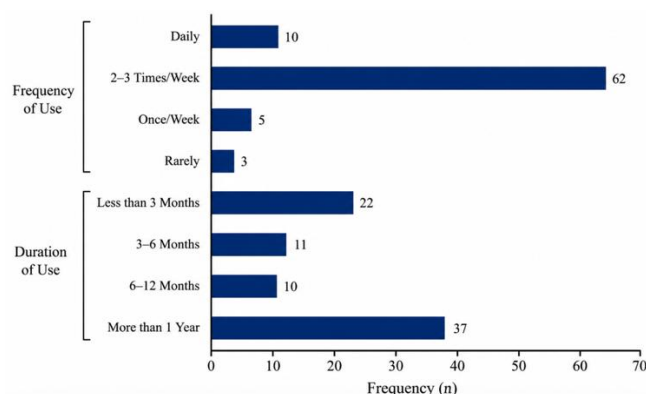


Figure 2. Students' ChatGPT usage characteristics.

Figure 2, the majority of college students use ChatGPT 2–3 times per week ($n = 62$; 77.5%). Meanwhile, only 10 college students (12.5%) use ChatGPT every day. The number of students who use ChatGPT once per week and rarely is only 5 students (6.3%) and 3 students (3.8%) respectively. This shows that ChatGPT has become a fairly frequently used tool in students' academic activities, although it has not yet become part of the daily routine of most respondents. The high proportion of using 2-3 times per week indicates that students are more likely to use ChatGPT to work on certain academic tasks, such as searching for information, translating articles, or compiling percentage assignments, rather than using it continuously every day.

Abbas *et al.* [20], found that the use of generative AI, including ChatGPT, has become a common practice among college students. This shows that students are actively utilizing ChatGPT to support academic activities and completion of learning assignments. These results are also in line with Abdaljawel *et al.* [21] which involved students from various countries. Students gave a positive attitude towards ChatGPT in relation to higher levels of use, as well as showing that the use of ChatGPT has become a widespread phenomenon in the higher education environment. These findings are supported by Rabiev *et al.* [22], reporting that most students use ChatGPT to help complete academic assignments, especially writing assignments and essays and 71.3% of students use ChatGPT which is used in academic assignments to help improve the quality of student work.

Figure 2, most college students have been using ChatGPT for more than a year ($n = 37$; 46.3%). Furthermore, 22 college students (27.5%) have been using ChatGPT for less than three months. The students who have used ChatGPT for 3-6 months and 6-12 months are 11 students (13.8%) and 10 students (12.5%) respectively.

The results showed that half of the students (respondents) had a long experience in using ChatGPT. A long enough use experience allows students to better understand the various features and functions of ChatGPT in supporting their academic activities. The existence of a number of students who have only used ChatGPT in less than three months shows that the adoption of this technology is still growing. The research sample includes both

experienced and new ChatGPT users, so the results of this study provide a more representative picture of students' perceptions of the use of ChatGPT.

Shahzad *et al.* [23], argue that the awareness, acceptance, and adoption of ChatGPT in higher education environments is growing as the user experience in interacting with the technology increases. Students who have used ChatGPT for a longer period of time tend to have a higher level of trust and acceptance of its benefits in supporting the learning process. Holland and Ciachir [24], show that students who have direct experience using ChatGPT in lecture activities generally provide a positive perception of the usefulness of the technology. Continuous user experience allows students to understand how ChatGPT can help complete academic assignments, obtain information quickly, and support the independent learning process.

The purpose of using ChatGPT by students is also the same as the results of the indicators. Since most college students report using ChatGPT in helping with academic assignments, translating articles, and searching for scientific references, it's natural that they find the tool useful for creating, analyzing, and evaluating academic writing assignments (Figure 3).

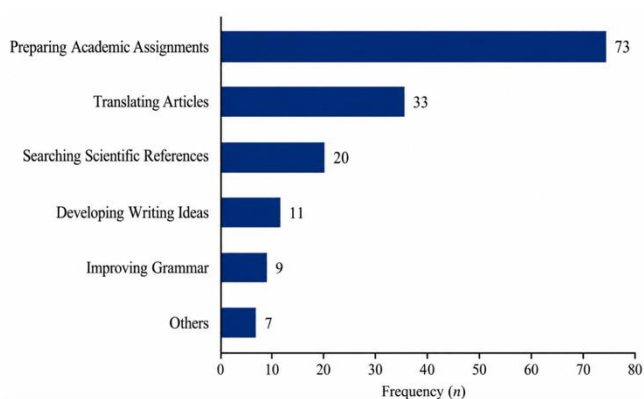


Figure 3. Purposes of ChatGPT use among students.

Most college students use ChatGPT to help draft academic assignments ($n = 73$), followed by translating articles ($n = 33$), looking for scientific references ($n = 20$), developing writing ideas ($n = 11$), improving grammar ($n = 9$), and other goals ($n = 7$). This shows that students use ChatGPT, especially in supporting various stages in academic writing, from information search to writing and revision. These findings are in line with the results of this study which shows that the indicators create the highest score (75.93%), followed by analyzing (72.38%) and evaluating (71.58%) (Figure 2). The high use of ChatGPT to compose academic assignments shows that students use this technology as a tool to generate ideas, compose writing frameworks, and develop academic paragraphs. This indicates that ChatGPT plays a role in supporting students' creative processes during the preparation of academic assignments.

Kasneci *et al.* [7], stated that ChatGPT has great potential to support the academic writing process, including generating ideas, structuring texts, and supporting student writing tasks. Choi *et al.* [8] found that college students use ChatGPT for writing assistance, such as helping to write essays, translating

academic texts, and improving grammar and language structure. This is also in line with Lo [9], reporting that generative AI is widely used by college students to brainstorm ideas, find initial references, and improve efficiency in academic writing. Thus, the use of ChatGPT in this study shows that ChatGPT plays a supporting role in the academic writing process, especially in the aspects of creating, analyzing, and evaluating thinking skills. Students who use ChatGPT frequently, have longer experience with this technology, and use it primarily for academic purposes show positive perceptions of its role in analyzing, evaluating, and creating academic content.

III. CONCLUSION

The results of this study show that ChatGPT is actively used by students in academic activities, especially for assignment preparation, article translation, and scientific reference search. This use shows that ChatGPT is one of the tools in the learning process that supports the efficiency of completing academic assignments. The results on the indicator show that the creative aspect obtains the highest score, followed by analyzing and evaluating. This indicates that ChatGPT is more widely used in the stage of developing ideas and preparing academic assignments. Thus, ChatGPT acts as a support tool that helps students develop thinking skills in scientific writing.

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REFERENCES

- [1] E. U. Eren, D. Atay, L. Atas Balci, Y. Sevim, and F. Eti Aslan, "The English language needs of health sciences students in Turkey," *Bati Anadolu Egitim Bilimleri Dergisi*, vol. 15, no. 2, pp. 1948–1968, 2024, doi: 10.51460/baed.1436231.
- [2] L. Garvey, G. Willetts, A. Herrmann, E. Verezub, and E. Sinchenko, "A multi-layered approach to developing academic written communication skills for nursing students," *International Journal of Nursing Education Scholarship*, vol. 20, no. 1, 2023, doi: 10.1515/ijnes-2022-0107.
- [3] T. N. Febriani, "Writing is challenging: Factors contributing to undergraduate students' difficulties in writing English essays," *Erudita: Journal of English Language Teaching*, vol. 2, no. 1, pp. 83–93, 2022, doi: 10.28918/erudita.v2i1.5441.
- [4] J. D. Gorospe and M. I. C. Rayton, "I can't write: Problems, factors, and recommendations," *Technium Social Sciences Journal*, vol. 31, no. 1, pp. 280–288, 2022, doi: 10.47577/tssj.v31i1.643.
- [5] A. Sahan, M. P. Saridewi, R. J. Wabang, and N. Adrianus, "Higher institution students' challenges in writing journal articles: Characteristics and proposed solutions," *English Review: Journal of English Education*, vol. 12, no. 1, pp. 269–282, 2024, doi: 10.25134/erjee.v12i1.8595.
- [6] A. L. Alkhaqani, "ChatGPT: How can it impact nursing and health science education?," *Al-Rafidain Journal of Medical Sciences*, vol. 5, pp. 112–113, 2023, doi: 10.54133/ajms.v5i.209.
- [7] E. Kasneci, K. Sessler, S. Küchemann, M. Bannert, D. Dementieva, *et al.*, "ChatGPT for good? On opportunities and challenges of large language models for education," *Learning and Individual Differences*, vol. 103, Art. no. 102274, 2023, doi: 10.1016/j.lindif.2023.102274.

- [8] J. H. Choi, K. E. Hickman, A. B. Monahan, and D. Schwarcz, "ChatGPT goes to law school," *Journal of Legal Education*, vol. 71, no. 3, pp. 387–400, 2022.
- [9] C. K. Lo, "What Is the Impact of ChatGPT on Education? A Rapid Review of the Literature," *Education Sciences*, vol. 13, no. 4, Art. no. 410, 2023, doi: 10.3390/educsci13040410
- [10] B. Rani, S. P. Srivastava, and S. Thakur, "Nursing education in the age of Chat Generative Pre-Trained Transformer: Current roles and future perspective," *Archives of Medicine and Health Sciences*, vol. 13, no. 1, pp. 145–148, 2024, doi: 10.4103/amhs.amhs_208_23.
- [11] M. E. A. Rahim, E. M. A. Rahim, N. A. Razawi, and N. Mohamed, "Students' perception on the use of ChatGPT as a language learning tool," *Ideology Journal of Arts and Social Science*, vol. 8, no. 2, pp. 70–78, 2023, doi: 10.24191/ideology.v8i2.456.
- [12] J. Zebua and C. V. Katemba, "Students' perceptions of using the OpenAI ChatGPT application in improving writing skills," *Journal of Language and Literature Studies*, vol. 4, no. 1, pp. 110–123, 2024, doi: 10.36312/jolls.v4i1.1805.
- [13] D. Hikmah and B. Walida, "The role of ChatGPT in enhancing students' critical thinking in academic writing," *Ethical Lingua*, vol. 11, no. 2, pp. 554–564, 2024, doi: 10.30605/25409190.780.
- [14] S. Mahapatra, "Impact of ChatGPT on ESL students' academic writing skills: A mixed methods intervention study," *Smart Learning Environments*, vol. 11, no. 9, pp. 1–18, 2024, doi: 10.1186/s40561-024-00295-9.
- [15] A. Boudouaia, S. Mouas, and B. Kouider, "A study on ChatGPT-4 as an innovative approach to enhancing English as a foreign language writing learning," *Journal of Educational Computing Research*, vol. 62, no. 6, pp. 1289–1317, 2024, doi: 10.1177/07356331241247465.
- [16] X. Zhao, A. Cox, and L. Cai, "ChatGPT and the digitisation of writing," *Humanities and Social Sciences Communications*, vol. 11, pp. 1–9, 2024, doi: 10.1057/s41599-024-02904-x.
- [17] J. Li, J. Huang, W. Wu, and P. B. Whipple, "Evaluating the role of ChatGPT in enhancing EFL writing assessment in classroom settings: A preliminary investigation," *Humanities and Social Sciences Communications*, vol. 11, pp. 1–9, 2024, doi: 10.1057/s41599-024-03755-2.
- [18] P. Polakova and P. Ivenz, "The impact of ChatGPT feedback on the development of EFL students' writing skills," *Cogent Education*, vol. 11, no. 1, pp. 1–12, 2024, doi: 10.1080/2331186X.2024.2410101.
- [19] Z. Bašić, A. Banovac, I. Kružić, and I. Jerković, "ChatGPT-3.5 as writing assistance in students' essays," *Humanities and Social Sciences Communications*, vol. 10, pp. 1–5, 2024, doi: 10.1057/s41599-023-02269-7.
- [20] M. Abbas, F. A. Jam, and T. I. Khan, "Is it harmful or helpful? Examining the causes and consequences of generative AI usage among university students," *International Journal of Educational Technology in Higher Education*, vol. 21, pp. 1–22, 2024, doi: 10.1186/s41239-024-00444-7.
- [21] M. Abdaljaleel, M. Barakat, M. Alsanafi, N. A. Salim, H. Abazid, et al., "A multinational study on the factors influencing university students' attitudes and usage of ChatGPT," *Scientific Reports*, vol. 14, pp. 1–14, 2024, doi: 10.1038/s41598-024-52549-8.
- [22] H. Rabiev, I. Sadidan, and N. A. S. Nurhidayah, "Exploring the usage of ChatGPT in academic assignments: Frequency, benefits, and perceptions among university students," in *Proceedings of the 5th International Conference on Information Technology and Security (IC-ITECHS)*, Malang, Indonesia, Sekolah Tinggi Informatika & Komputer Indonesia (STIKI), pp. 465–469, 2024, published by LPPM, Universitas Bhinneka Nusantara, doi: 10.32664/ic-itech.v5i1.1669.
- [23] M. F. Shahzad, S. Xu, and I. Javed, "ChatGPT awareness, acceptance, and adoption in higher education: The role of trust as a cornerstone," *International Journal of Educational Technology in Higher Education*, vol. 21, pp. 1–24, 2024, doi: 10.1186/s41239-024-00478-x.
- [24] A. Holland and C. Ciachir, "A qualitative study of students' lived experience and perceptions of using ChatGPT: Immediacy, equity and integrity," *Interactive Learning Environments*, vol. 33, pp. 483–494, 2025, doi: 10.1080/10494820.2024.2350655

Generative AI for Stunting Prevention Education: Enhancing Maternal Knowledge and Awareness in Samosir Regency, Indonesia

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ABSTRACT

Background: Stunting remains a major public health challenge worldwide, particularly in low- and middle-income countries, including Indonesia. Maternal knowledge and awareness regarding nutrition, infant feeding practices, sanitation, and child health are essential determinants in preventing stunting. The advancement of Artificial Intelligence, especially Generative AI, offers a novel approach to health education by providing interactive, personalized, and accessible learning experiences.

Objective: This study aimed to evaluate the effectiveness of Generative AI-based stunting prevention education in improving maternal knowledge and awareness in Samosir Regency, Indonesia.

Methods: A quasi-experimental study with a pre-test and post-test control group design was conducted among 100 mothers in Samosir Regency in 2025. Participants were divided into an intervention group (n=50) receiving AI-based stunting education for four weeks and a control group (n=50) receiving conventional health education. Maternal knowledge and awareness were measured using validated questionnaires. Data were analyzed using paired and independent t-tests with a 95% confidence interval.

Results: The intervention group demonstrated significant improvements in knowledge scores (from 56.48 ± 10.25 to 85.76 ± 8.14 ; $p < 0.001$) and awareness scores (from 58.92 ± 9.87 to 88.34 ± 7.92 ; $p < 0.001$). The control group showed smaller improvements in knowledge (55.84 ± 9.76 to 65.28 ± 9.15 ; $p < 0.05$) and awareness (57.76 ± 10.42 to 66.54 ± 8.86 ; $p < 0.05$). Post-test comparison showed significantly higher scores in the intervention group than the control group ($p < 0.001$).

Conclusion: Generative AI-based health education is more effective than conventional methods in improving maternal knowledge and awareness regarding stunting prevention. Integrating AI technology into community health programs may support efforts to reduce stunting prevalence.

I. INTRODUCTION

Stunting remains one of the most serious public health problems in the world. According to the World Health Organization (WHO), stunting is a growth and developmental disorder in children caused by chronic

malnutrition, recurrent infections, and inadequate psychosocial stimulation, characterized by a child's length or height being below the standard for their age. This condition not only affects physical growth but also leads to impaired cognitive development, reduced academic performance, decreased productivity in adulthood, and an increased risk of non-communicable diseases later in life. Therefore, stunting prevention has become a global health priority and an essential part of the sustainable development agenda.

Globally, WHO estimates that around 148 million children under five were affected by stunting in 2022. Although the global prevalence of stunting shows a declining trend, this figure still indicates that nearly one in five children worldwide experiences growth impairment due to chronic malnutrition. This condition is a major concern as stunting can hinder the development of human resources quality and negatively impact a country's economic development.

In Indonesia, stunting remains a significant public health issue requiring comprehensive interventions. The results of the Indonesian Nutrition Status Survey (SSGI) in 2024 showed that the national stunting prevalence reached 19.8%, a decrease compared to 21.5% in 2023. Although this decline exceeded the 2024 national target of 20.1%, the figure is still above the National Medium-Term Development Plan (RPJMN) target of 14.2% by 2029. In addition, the Ministry of Health of the Republic of Indonesia reported that North Sumatra Province is among the six provinces with the highest number of stunted children under five, with an estimated 316,456 cases. This indicates that accelerated stunting reduction still requires innovative and sustainable strategies (Ministry of Health of the Republic of Indonesia, 2024).

At the provincial level, North Sumatra still faces challenges in reducing stunting prevalence. Based on the 2023 Indonesia Health Survey (SKI), the stunting prevalence in North Sumatra Province was 18.9%. As the provincial capital, Medan City has implemented various

acceleration programs to reduce stunting through strengthening maternal and child health services, nutrition education, increasing specific and sensitive interventions, and utilizing information technology in health promotion. However, gaps in knowledge and awareness regarding optimal stunting prevention practices are still found among the community, particularly among mothers with children under five (Ministry of Health of the Republic of Indonesia, 2024).

Samosir Regency, as one of the districts in North Sumatra Province, has a geographical characteristic of island and highland areas that may affect community access to health services and health information. Limited access to quality information may lead to low maternal knowledge and awareness regarding stunting prevention, particularly related to balanced nutrition, exclusive breastfeeding, appropriate complementary feeding (MP-ASI), child growth monitoring, and the implementation of clean and healthy living behaviors. In fact, various studies have shown that maternal knowledge and awareness are key determinants in stunting prevention among children under five (Ministry of Health of the Republic of Indonesia, 2024).

So far, stunting prevention education has generally been conducted using conventional methods such as health counseling and leaflet distribution. However, these methods still have several limitations, including being one-way, less interactive, and restricted by time and place. As a result, the health information received by mothers is not always well understood and has not been able to encourage sustainable behavior change. Therefore, innovative, more adaptive, interactive, and easily accessible educational methods are needed.

The development of digital technology, particularly Artificial Intelligence (AI), opens new opportunities for transforming education and public health promotion. One of the latest advancements is Generative Artificial Intelligence (Generative AI), a technology capable of generating information and providing interactive responses according to user needs. In the health sector, Generative AI has the potential to provide more personalized, responsive, and accessible education at any time. The utilization of this technology allows mothers to obtain continuous information on stunting prevention tailored to their level of understanding and individual needs, thereby improving knowledge and awareness more effectively compared to conventional educational methods.

Based on the above background, the research problem of this study is the implementation of Generative AI-based stunting prevention education on improving mothers' knowledge and awareness in Samosir Regency in 2025. The aim of this study is to analyze more deeply the effectiveness of Generative AI-based stunting prevention education in improving mothers' knowledge and awareness.

II. RESEARCH METHODOLOGY

This study employed a quasi-experimental design with a pre-test and post-test control group design involving 100 mothers of children under five (under-five children's mothers). The participants were divided into two groups: 50

respondents in the intervention group and 50 respondents in the control group.

The intervention group received stunting prevention education through a Generative AI-based application for four weeks, while the control group received conventional education through health counseling sessions and leaflet distribution.

The findings of this study are expected to provide scientific evidence regarding the effectiveness of Generative AI utilization as an innovative health education tool in supporting the acceleration of stunting reduction in Samosir Regency. Furthermore, it is anticipated that this approach can serve as an applicable intervention model that can be implemented in various regions across Indonesia (Ministry of Health of the Republic of Indonesia, 2024).

III. RESULTS OF THE STUDY

This study involved 100 respondents, consisting of 50 mothers in the intervention group who received Generative AI-based stunting prevention education and 50 mothers in the control group who received conventional education in the form of counseling and leaflet distribution. The analysis of the study results included respondents' characteristics, changes in knowledge and awareness levels before and after the intervention, and comparison of the effectiveness of both educational methods.

A. Respondents' Characteristics

Table 1 Distribution of Respondents' Characteristics by Study Group (n = 100)

Characteristics	Intervention (n = 50)	Control (n = 50)	Total (n = 100)
Maternal Age			
< 25 years	10 (20.0%)	12 (24.0%)	22 (22.0%)
25–35 years	30 (60.0%)	28 (56.0%)	58 (58.0%)
> 35 years	10 (20.0%)	10 (20.0%)	20 (20.0%)
Education			
Elementary–Junior High School	12 (24.0%)	14 (28.0%)	26 (26.0%)
Senior High School	26 (52.0%)	25 (50.0%)	51 (51.0%)
College/University	12 (24.0%)	11 (22.0%)	23 (23.0%)
Occupation			
Housewife	32 (64.0%)	34 (68.0%)	66 (66.0%)
Farmer	10 (20.0%)	8 (16.0%)	18 (18.0%)
Employed/Self-employed	8 (16.0%)	8 (16.0%)	16 (16.0%)
Number of Children			
1 child	21 (42.0%)	18 (36.0%)	39 (39.0%)
2 children	20 (40.0%)	23 (46.0%)	43 (43.0%)
≥ 3 children	9 (18.0%)	9 (18.0%)	18 (18.0%)

Based on Table 1, most respondents were in the age group of 25–35 years (58%), had completed senior high school education (51%), were housewives (66%), and had two children (43%). The distribution of characteristics between

the intervention and control groups was relatively balanced, indicating that both groups were comparable for evaluating the effect of the Generative AI-based educational intervention.

B. Differences in Knowledge Levels Before and After the Intervention

Table 2 Comparison of Maternal Knowledge and Awareness Scores Before and After the Intervention by Study Group (n = 100)

Group	Pre-test (Mean $\pm$ SD)	Post-test (Mean $\pm$ SD)	Mean Difference (Δ)	p-value
Intervention (Generative AI)	56.48 $\pm$ 10.25	85.76 $\pm$ 8.14	+29.28	< 0.001
Control (Conventional Education)	55.84 $\pm$ 9.76	65.28 $\pm$ 9.15	+9.44	0.021

The results of the paired t-test showed a statistically significant increase in maternal knowledge scores after receiving Generative AI-based education ($p < 0.001$). The mean knowledge score increased by 29.28 points, shifting from the “moderate” category to the “good” category.

The findings indicate that both groups experienced an improvement in maternal knowledge and awareness after the educational intervention. However, the increase in the intervention group, which received Generative AI-based education (+29.28 points), was substantially higher than that of the control group, which received conventional education (+9.44 points). In addition, the improvement in both groups was statistically significant ($p < 0.05$), with the intervention group showing a stronger level of significance ($p < 0.001$). These findings suggest that Generative AI-based stunting prevention education is more effective in improving maternal knowledge and awareness compared to conventional educational methods.

C. Differences in Maternal Awareness Levels Before and After the Intervention

Table 3 Changes in Maternal Awareness Scores Before and After the Intervention (n = 100)

Group	Pre-test (Mean $\pm$ SD)	Post-test (Mean $\pm$ SD)	Mean Difference (Δ)	p-value
Intervention (Generative AI)	58.92 $\pm$ 9.87	88.34 $\pm$ 7.92	+29.42	< 0.001
Control (Conventional Education)	57.76 $\pm$ 10.42	66.54 $\pm$ 8.86	+8.78	0.034

The results of the study indicate that maternal awareness regarding stunting prevention increased in both groups following the educational intervention. The intervention group, which received Generative AI-based education, showed a substantial increase in the mean awareness score of 29.42 points, from 58.92 $\pm$ 9.87 to 88.34 $\pm$ 7.92 ($p < 0.001$). Meanwhile, the control group, which received conventional education, demonstrated an increase of 8.78 points, from 57.76 $\pm$ 10.42 to 66.54 $\pm$ 8.86 ($p = 0.034$).

These findings suggest that both educational approaches were effective in improving maternal awareness. However, the magnitude of improvement in the intervention group was considerably higher than that of the control group. This indicates that Generative AI-based education is more effective in increasing maternal awareness regarding stunting prevention compared to conventional educational methods.

D. Comparison of Intervention and Control Effectiveness After the Educational Program

Table 4 Comparison of Post-test Knowledge and Awareness Scores Between Intervention and Control Groups (n = 100)

Variable	Intervention Group (Mean $\pm$ SD)	Control Group (Mean $\pm$ SD)	p-value
Knowledge	85.76 $\pm$ 8.14	65.28 $\pm$ 9.15	< 0.001
Awareness	88.34 $\pm$ 7.92	66.54 $\pm$ 8.86	< 0.001

The analysis showed that the mean post-test knowledge score in the intervention group (85.76 $\pm$ 8.14) was significantly higher than that of the control group (65.28 $\pm$ 9.15), with a p-value of < 0.001 . Similarly, the mean post-test awareness score in the intervention group (88.34 $\pm$ 7.92) was also significantly higher compared to the control group (66.54 $\pm$ 8.86), with a statistically significant difference ($p < 0.001$).

These findings indicate that Generative AI-based stunting prevention education is more effective than conventional educational methods in improving both knowledge and awareness among mothers regarding stunting prevention in Samosir Regency.

IV. DISCUSSION

This study demonstrates that Generative AI-based stunting prevention education significantly improves maternal knowledge and awareness compared to conventional education. These findings are supported by a quasi-experimental pre-test and post-test with control group design, which showed greater improvements in the intervention group for both knowledge and awareness variables.

A. Improvement in Maternal Knowledge on Stunting

The results showed an increase in knowledge in the intervention group from 56.48 $\pm$ 10.25 to 85.76 $\pm$ 8.14 (Δ +29.28; $p < 0.001$), which was substantially higher than the control group, which increased from 55.84 $\pm$ 9.76 to 65.28 $\pm$ 9.15 (Δ +9.44; $p = 0.021$).

These findings are consistent with Pratiwi *et al.* (2022) in Central Java, who reported that digital-based education media (videos and nutrition education applications) significantly improved maternal knowledge about child nutrition compared to conventional counseling. In that study, the intervention group showed higher knowledge

gains because the materials could be accessed repeatedly and were easier to understand.

Similarly, Sari & Dewi (2021) found that application-based health education significantly improved maternal understanding of complementary feeding (MP-ASI) and stunting prevention compared to leaflets. This supports the present study that digital approaches provide higher educational effectiveness.

B. Improvement in Maternal Awareness

For awareness, the intervention group increased from 58.92 ± 9.87 to 88.34 ± 7.92 ($p < 0.001$), while the control group increased from 57.76 ± 10.42 to 66.54 ± 8.86 ($p = 0.034$).

This is in line with Wulandari *et al.* (2023), who reported that mobile health-based educational interventions improved maternal awareness of stunting prevention by enhancing risk perception and parenting motivation. Increased awareness was attributed to stronger user-media interaction.

Furthermore, Kusuma *et al.* (2022) stated that interactive health education is more effective in improving health awareness than one-way lectures because it enables active user participation in the learning process.

C. Comparison of Generative AI and Conventional Education Effectiveness

Post-test results revealed a highly significant difference between intervention and control groups ($p < 0.001$) for both knowledge and awareness, indicating that Generative AI-based education is more effective than conventional methods.

This is supported by Lee *et al.* (2023), who found that AI chatbot-based health education improves information retention and user engagement compared to traditional education methods. AI enables real-time responses and personalized learning. Similarly, Nguyen *et al.* (2024) in Southeast Asia reported that AI-based health education enhances effectiveness by providing a more personalized and adaptive learning experience.

D. Advantages of Generative AI in Health Education

Generative AI offers several advantages that explain the findings of this study, including:

- Two-way interactive communication (educational dialogue)
- Personalized information based on user needs
- 24-hour accessibility without time limitations
- Simplification of complex medical information
- Ability to respond to specific user questions

This aligns with the theory of digital health education, which states that AI-based learning improves engagement and comprehension through adaptive learning systems.

In the context of stunting in Indonesia, Rachman *et al.* (2021) reported that conventional education through Posyandu still has limitations in achieving long-term behavioral change due to low exposure intensity.

Meanwhile, Hidayat *et al.* (2023) found that digital nutrition education applications improve maternal compliance in child growth monitoring, although not yet utilizing Generative AI specifically. Thus, this study strengthens evidence that more advanced digital approaches such as Generative AI have greater potential than conventional digital tools.

E. Study Limitations

This study has several limitations:

- Relatively short intervention duration (4 weeks)
- Focused only on knowledge and awareness, not long-term behavioral changes
- Dependence on participants' digital literacy

Therefore, further studies are needed to assess the long-term sustainability of Generative AI interventions on stunting prevention behavior.

V. CONCLUSION AND RECOMMENDATIONS

A. Conclusion

This study aimed to analyze the effectiveness of Generative Artificial Intelligence (Generative AI)-based stunting prevention education in improving maternal knowledge and awareness in Samosir Regency in 2025. Based on a quasi-experimental pre-test and post-test with control group design involving 100 respondents, it can be concluded that Generative AI-based education is more effective than conventional education in improving maternal understanding of stunting prevention.

The intervention group showed a significant increase in knowledge scores from 56.48 ± 10.25 to 85.76 ± 8.14 ($p < 0.001$), as well as awareness scores from 58.92 ± 9.87 to 88.34 ± 7.92 ($p < 0.001$). Meanwhile, the control group also experienced improvements, but with smaller changes.

These findings indicate that the characteristics of Generative AI—such as interactivity, personalized information delivery, 24-hour accessibility, and two-way communication—enhance maternal learning regarding the first 1,000 days of life, exclusive breastfeeding, complementary feeding, immunization, sanitation, and child growth monitoring.

More broadly, the use of digital and AI technologies in health education has strong potential to strengthen stunting prevention programs, as stunting remains a global health issue affecting millions of children. Reports from UNICEF–WHO–World Bank highlight that innovative strategies are needed to accelerate child nutrition improvement.

B. Recommendations

For Local Government and Health Office of Samosir Regency

Local governments are encouraged to develop AI-based health education platforms to support Posyandu, Primary Health Centers, and stunting reduction programs. AI systems designed with simple language and local cultural adaptation may improve community acceptance.

For Health Workers and Posyandu Cadres

Health workers may utilize Generative AI as a supporting tool for nutrition counseling, antenatal classes, and child growth monitoring to ensure continuous health education delivery.

For Future Researchers

Future studies are recommended to use larger sample sizes, longer intervention periods, and include behavioral and child nutritional status indicators to assess the long-term impact of AI-based interventions on stunting reduction.

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REFERENCES

- [1] Beal, T., Tumilowicz, A., Sutrisna, A., Izwardy, D., & Neueld, L. M. (2018). A review of child stunting determinants in Indonesia. *Maternal & Child Nutrition*, 14(4), e12617.
- [2] Faridah, F., Anies, A., Kartasurya, M. I., & Widjanarko, B. (2024). Online educational intervention: Improving maternal knowledge and attitudes in providing developmental stimulation for stunting toddlers. *Narra Journal*, 4(1).
- [3] Nudrat, S., Mufti, T., Sohail, S. S., & Madsen, D. Ø. (2024). ChatGPT as an innovative heutigological tool in medical education. *Cogent Education*.
- [4] Aulia, E. S., *et al.* (2024). Chatbots Be Nutritionists: Exploring the Potential of AI-Powered Chatbots to Improve Nutritional Counseling in Indonesia. *Jurnal Sosioteknologi*.
- [5] Hasan, D. S., & Arief, Y. S. (2024). Mobile application intervention to improve nutritional literacy of mothers with stunting children: A systematic review. *Pedimatern Nursing Journal*.
- [6] Erika, K. A., *et al.* (2024). Stunting Super App as an Effort Toward Stunting Management in Indonesia: Delphi and Pilot Study. *JMIR Human Factors*.
- [7] Kasneci, E., Sessler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., *et al.* (2023). ChatGPT for good? On opportunities and challenges of large language models for education. *Learning and Individual Differences*, 103, 102274.
- [8] Saraswati, D., Wahyuni, F., & Wynda Myke Nola, M. (2025). Stunting Prevention: Fulfillment of Nutrition, Health Education and Socioeconomic Status in Efforts to Overcome Nutritional Problems in Toddlers. *Faletehan Health Journal*, 12(2), 160–166.
- [9] Murray, E., Hekler, E. B., Andersson, G., Collins, L. M., Doherty, A., Hollis, C., *et al.* (2019). Evaluating digital health interventions: Key questions and approaches. *American Journal of Preventive Medicine*, 51(5), 843–851.
- [10] Rosenstock, I. M. (1974). Historical origins of the Health Belief Model. *Health Education Monographs*, 2(4), 328–335.
- [11] Sung, Y. T., Chang, K. E., & Liu, T. C. (2016). The effects of integrating mobile devices with teaching and learning on students' learning performance: A meta-analysis and research synthesis. *Computers & Education*, 94, 252–275.
- [12] UNICEF. (2023). Nutrition and Child Malnutrition in Indonesia. UNICEF Indonesia.
- [13] Wahyuni, F. (2025). Pemberdayaan Masyarakat di Kampung Keluarga Berkualitas (Kampung KB) Dalam Fortikasi Pangan Lokal Sebagai Upaya Pencegahan Stunting. *Jurnal Kesehatan Global*, 8(1).
- [14] Wahyuni, F. (2025). Strengthening the Role of Husbands in Preventing Anemia Among Pregnant Women in 2025. *JURNAL KEPERAWATAN DAN FISIOTERAPI (JKF)*, 8(1), 63–67.
- [15] Wahyuni, F., Kencana, T., Darmayanti, E., Sipahutar, D. M., & Fithri, N. (2023). No TitleThe Perceptions of Pregnant Mothers on Exclusive Breastfeeding: Motivation to Perform Early Breastfeeding Initiation (EBI) at Hayati Clinic Medan. *The Malaysian Journal of Nursing (MJN)*, <https://doi.org/10.35451/5agjm050>
- [16] World Health Organization (WHO). (2023). Levels and Trends in Child Malnutrition: UNICEF/WHO/World Bank Joint Child Malnutrition Estimates 2023 Edition. Geneva: WHO.
- [17] World Health Organization (WHO). (2025). Joint Child Malnutrition Estimates: Key Findings 2025 Edition. Geneva: WHO.
- [18] World Bank. (2023). World Bank Supports Indonesia's Efforts to Accelerate Childhood Stunting Reduction. Washington, DC: World Bank.
- [19] Tanwir, T., Hidjah, K., & Susilowati, D. (2025). Implementasi Konsultasi Stunting Balita Menggunakan Large Language Models (LLMs). *Reputasi : Jurnal Rekayasa Perangkat Lunak*.

Exploring the Role of ChatGPT as an Emotional Support Tool for Generation Z Students Coping with Psychological Stress

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ABSTRACT — The increasing use of artificial intelligence (AI) has transformed not only educational practices but also the way individuals seek emotional support. Among Generation Z students, ChatGPT has emerged as a readily accessible platform for discussing personal concerns, managing stress, and seeking guidance. This study aimed to explore the role of ChatGPT as an emotional support tool among Generation Z students experiencing psychological stress. Guided by Lazarus and Folkman's Stress and Coping Theory, this research investigated how students utilized ChatGPT to cope with academic pressures, interpersonal challenges, and daily stressors. A quantitative survey design was employed involving undergraduate students from higher education institutions. Data were collected through an online questionnaire measuring frequency of ChatGPT use, perceived emotional support, and psychological stress levels. The findings revealed that emotional expression was the most prominent function of ChatGPT among Generation Z students ($M = 4.12$), followed by cognitive coping ($M = 3.98$) and perceived emotional support ($M = 3.87$). Significant positive relationships were found between ChatGPT use, perceived emotional support ($r = .62, p < .001$), and coping ability ($r = .58, p < .001$). The results suggest that ChatGPT serves as a complementary emotional support tool that assists students in coping with psychological stress while highlighting the importance of maintaining human-based support systems and professional mental health services.

KEYWORDS: ChatGPT, Emotional Support, Generation Z, Psychological Stress.

I. INTRODUCTION

The rapid advancement of Artificial Intelligence (AI) has transformed various aspects of human life, including education, communication, healthcare, and psychological well-being. Among the emerging AI technologies, ChatGPT has gained remarkable popularity due to its ability to generate human-like responses, provide information, and engage in interactive conversations. Initially developed as an intelligent conversational tool for information retrieval and problem-solving, ChatGPT has increasingly been utilized for purposes beyond academic and professional assistance. In recent years, many users have begun employing ChatGPT as a source of emotional support, seeking advice, reassurance, and guidance when experiencing personal difficulties.

Generation Z, generally defined as individuals born between the mid-1990s and early 2010s, represents the first generation to grow up fully immersed in digital technologies.

As digital natives, Generation Z students rely heavily on technology for learning, communication, social interaction, and entertainment. While digital technology provides numerous opportunities, Generation Z also faces various psychological challenges that may affect their mental well-being. University students frequently encounter psychological stress resulting from academic demands, assignment deadlines, examinations, family expectations, financial pressures, interpersonal conflicts, and uncertainties regarding future careers. When such stressors accumulate, students often seek coping mechanisms to manage their emotional and psychological conditions.

Traditionally, emotional support has been obtained through interpersonal interactions with family members, friends, counselors, psychologists, or other trusted individuals. However, changes in communication patterns and the widespread accessibility of digital technology have altered how young people seek assistance during stressful situations. Many students may hesitate to discuss their personal concerns with others due to fear of judgment, stigma, privacy concerns, or limited access to professional mental health services. Consequently, digital platforms have emerged as alternative sources of support, offering accessibility, anonymity, convenience, and immediate responses.

Among these digital platforms, ChatGPT has become increasingly popular as an informal emotional support resource. Students frequently use ChatGPT to express their feelings, discuss personal concerns, seek advice regarding stressful situations, obtain motivational encouragement, and explore possible solutions to their problems. Unlike traditional support systems, ChatGPT is available at any time, responds instantly, and allows users to communicate without fear of social evaluation. These characteristics make ChatGPT an attractive option for students seeking immediate emotional assistance during periods of psychological distress.

Despite the growing use of ChatGPT for emotional and psychological purposes, existing research has predominantly focused on its educational applications. Previous studies have examined the effectiveness of ChatGPT in supporting learning activities, enhancing academic performance, improving writing skills, facilitating language learning, and promoting educational innovation. While such studies have provided valuable insights into the academic benefits of AI

technologies, relatively limited attention has been directed toward understanding how students utilize ChatGPT as a source of emotional support and coping assistance.

This limitation is particularly important given the increasing prevalence of psychological stress among university students and the growing tendency of Generation Z to integrate AI technologies into their daily lives. The emergence of AI-mediated emotional support raises several important questions. Why do students choose ChatGPT as a source of emotional support? What types of psychological stress encourage students to seek assistance from ChatGPT? How effective do students perceive ChatGPT to be in helping them cope with emotional challenges? Furthermore, what opportunities and limitations exist when AI technologies are used as emotional support tools?

Drawing upon Lazarus and Folkman's Stress and Coping Theory, this study seeks to explore the role of ChatGPT as an emotional support tool among Generation Z students coping with psychological stress. According to the theory, individuals employ various coping strategies to manage stressful situations and maintain psychological well-being. In the context of contemporary digital environments, ChatGPT may represent a new form of coping resource that students utilize when facing emotional difficulties. Understanding this phenomenon is important not only for advancing knowledge in psychology and digital technology but also for informing educators, mental health practitioners, and policymakers about the potential role of AI in supporting student well-being.

Therefore, this study aims to explore how Generation Z students use ChatGPT for emotional support, examine their perceptions regarding its effectiveness, and identify both the benefits and limitations of AI-mediated emotional support. The findings are expected to contribute to the growing literature on digital mental health, artificial intelligence, and psychological coping strategies among young adults in the digital era.

To understand this phenomenon, this study is grounded in Stress and Coping Theory proposed by Lazarus and Folkman (1984), which explains how individuals respond to stressful situations through various coping strategies aimed at managing emotional and psychological distress. In today's digital environment, the use of ChatGPT may represent a contemporary coping resource that students utilize to seek emotional support, guidance, and reassurance when facing psychological stress. Therefore, this study explores the role of ChatGPT as an emotional support tool among Generation Z students and examines its potential contribution to students' coping processes and psychological well-being.

A. Research Question

1. How do generation Z university students use CHATGPT as an emotional support tool when coping with psychological stress?
2. What role does CHATGPT play in supporting Generation Z university students in coping with psychological stress?

II. LITERATURE REVIEW

A. Artificial Intelligence and ChatGPT

Artificial Intelligence (AI) refers to the capability of computer systems to perform tasks that typically require human intelligence, including learning, reasoning, decision-making, and language processing. The rapid advancement of AI technologies has significantly transformed the way individuals communicate, learn, and seek information.

One of the most widely adopted AI applications is ChatGPT, a generative AI chatbot developed by OpenAI. ChatGPT utilizes natural language processing (NLP) and large language models to generate human-like responses in conversational settings. While initially designed to assist users with information retrieval, problem-solving, and educational tasks, ChatGPT has increasingly been utilized for emotional and psychological purposes.

Recent observations suggest that users frequently engage with ChatGPT not only for academic assistance but also for discussing personal concerns, seeking reassurance, expressing emotions, and obtaining advice during stressful situations. This emerging phenomenon has expanded the role of AI from an informational tool to a potential source of emotional support.

B. Generation Z in the Digital Era

Generation Z refers to individuals born approximately between 1997 and 2012. Unlike previous generations, Generation Z has been exposed to digital technology from an early age, earning them the label of digital natives.

According to Prensky (2001), digital natives demonstrate distinctive patterns of communication, information-seeking behavior, and technology adoption. They are highly dependent on digital platforms for education, social interaction, entertainment, and emotional expression.

Research indicates that Generation Z is more likely to seek support through digital channels due to accessibility, anonymity, and convenience. Consequently, AI-powered communication platforms such as ChatGPT have become integrated into their daily coping behaviors and emotional regulation processes.

C. Psychological Stress among University Students

Psychological stress refers to an emotional and cognitive response that occurs when individuals perceive environmental demands as exceeding their available coping resources. According to Lazarus and Folkman (1984), stress results from an individual's appraisal of a situation rather than from the event itself. University students are particularly vulnerable to psychological stress due to academic responsibilities, social expectations, financial concerns, and uncertainties regarding future careers.

Among university students, psychological stress commonly originates from several sources. Academic stress may arise from examinations, assignment deadlines, academic competition, and concerns about academic achievement. Family-related stress may stem from parental expectations, interpersonal conflicts, and financial difficulties. Additionally, career-related stress emerges from concerns regarding employability, career readiness, and future professional opportunities. If not effectively

managed, prolonged psychological stress may negatively affect students' emotional well-being, academic performance, and overall mental health.

D. Emotional Support

Emotional support is one of the most important forms of social support in psychological well-being.

According to House (1981), emotional support refers to expressions of empathy, understanding, caring, reassurance, trust, and encouragement provided to individuals experiencing difficulties.

Emotional support contributes to:

- reducing feelings of loneliness
- enhancing self-confidence
- improving emotional regulation
- reducing stress and anxiety

Traditionally, emotional support is obtained from family members, friends, counselors, and mental health professionals. However, technological advancements have expanded emotional support sources to include digital communities, online platforms, and conversational AI systems.

The increasing use of ChatGPT for emotional conversations suggests that AI may serve as a supplementary emotional support resource, particularly among digitally connected generations.

E. Stress and Coping Theory

This study is grounded in the Stress and Coping Theory developed by Lazarus and Folkman (1984), which explains how individuals evaluate and respond to stressful situations. According to the theory, stress does not arise solely from external events but from an individual's cognitive appraisal of those events and their perceived ability to cope with them. The theory emphasizes that individuals actively interpret stressful experiences and employ various coping strategies to manage psychological distress.

The first stage of the coping process is known as primary appraisal, in which individuals evaluate whether a particular situation is irrelevant, benign, or stressful. During this stage, a person determines the significance of an event and assesses its potential impact on their well-being. For example, a university student facing multiple assignment deadlines, examinations, and academic responsibilities may perceive these demands as threatening or overwhelming, thereby experiencing psychological stress.

Following primary appraisal, individuals engage in secondary appraisal, a process through which they assess their available resources and coping capabilities. At this stage, individuals consider whether they possess sufficient skills, support systems, or external resources to manage the stressful situation effectively. Students experiencing psychological stress may seek assistance from family members, friends, counselors, or other support networks. In today's digital environment, technological resources such as ChatGPT may also be perceived as accessible and readily available sources of support, information, and guidance.

According to Lazarus and Folkman (1984), coping refers to the cognitive and behavioral efforts employed to manage internal and external demands that are perceived as stressful. The theory distinguishes between two primary forms of coping: problem-focused coping and emotion-focused coping. Problem-focused coping involves efforts to address the source of stress directly by seeking information, identifying solutions, planning actions, and making decisions. In this context, students may use ChatGPT to obtain recommendations, explore possible solutions, organize tasks, or gain information that helps them manage academic and personal challenges more effectively.

In contrast, emotion-focused coping aims to regulate emotional responses associated with stressful experiences. Individuals may seek comfort, reassurance, emotional expression, or psychological relief when facing distressing situations. For Generation Z students, ChatGPT may provide a space to express frustrations, discuss worries, reflect on personal concerns, and receive supportive responses that contribute to emotional regulation. Although ChatGPT cannot replace professional psychological services, its accessibility, anonymity, and immediate responsiveness may encourage students to utilize it as a supplementary coping resource during periods of psychological stress.

Within the framework of Stress and Coping Theory, the use of ChatGPT can therefore be understood as a contemporary coping mechanism that supports both problem-focused and emotion-focused coping processes. By providing information, guidance, reassurance, and opportunities for emotional expression, ChatGPT may play a role in helping Generation Z students manage psychological stress and navigate everyday challenges in the digital era.

F. AI-Mediated Emotional Support and Social Support Theory

The concept of AI-mediated emotional support can be understood through Social Support Theory, which emphasizes the importance of supportive interactions in helping individuals cope with stress and maintain psychological well-being. According to House (1981), emotional support includes empathy, understanding, reassurance, encouragement, and expressions of care.

Recent advances in conversational artificial intelligence have enabled individuals to seek support through interactions with AI systems such as ChatGPT. Although AI lacks genuine emotions and human experiences, its ability to provide immediate, personalized, and non-judgmental responses has made it an increasingly popular source of informal emotional support. Students may use ChatGPT to discuss personal concerns, express emotions, seek reassurance, and obtain guidance during stressful situations.

From the perspective of Stress and Coping Theory (Lazarus & Folkman, 1984), ChatGPT can be viewed as a supplementary coping resource that supports both emotion-focused coping and problem-focused coping processes. However, scholars emphasize that AI should complement rather than replace professional mental health services and interpersonal support networks.

G. Previous Studies and Research Gap

Previous studies have primarily focused on the educational applications of ChatGPT and generative artificial intelligence. Kasneci *et al.* (2023) highlighted the opportunities and challenges of ChatGPT in educational settings, while Cotton *et al.* (2023) discussed its implications for academic integrity and learning practices. Similarly, Tlili *et al.* (2023) examined the broader impact of generative AI on higher education.

Beyond education, emerging studies have explored the potential of conversational AI in supporting mental health and psychological well-being. Abd-Alrazaq *et al.* (2023) suggested that AI chatbots may provide accessible psychological support, while Inkster *et al.* (2018) demonstrated the effectiveness of chatbot-based interventions in reducing psychological distress.

Despite these developments, limited empirical research has specifically investigated how Generation Z university students utilize ChatGPT as an emotional support tool during experiences of psychological stress. Most existing studies focus on educational outcomes or clinical mental health interventions, leaving a gap in understanding the everyday use of ChatGPT as a coping resource among students. Therefore, this study seeks to address this gap by examining the role of ChatGPT as an emotional support tool among Generation Z students coping with psychological stress.

H. Conceptual Framework

Based on Stress and Coping Theory and Social Support Theory, this study proposes that ChatGPT functions as a technology-mediated emotional support tool for Generation Z students experiencing psychological stress. When students encounter psychological stress, they may use ChatGPT to express emotions, seek guidance, and receive reassurance. These interactions are expected to contribute to perceived emotional support and facilitate students' coping processes.

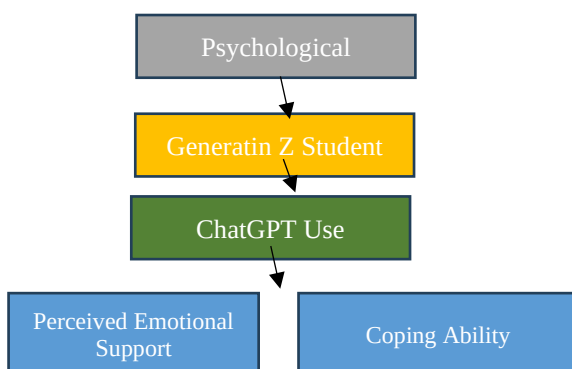


Figure 1. Conceptual Framework of the Study.

III. RESEARCH DESIGN

This study employed a quantitative research approach using a cross-sectional survey design to explore the role of ChatGPT as an emotional support tool among Generation Z students coping with psychological stress. A quantitative approach was considered appropriate because it allows researchers to systematically measure and analyze students'

perceptions, experiences, and behaviors regarding the use of ChatGPT for emotional support.

The study is grounded in the Stress and Coping Theory developed by Lazarus and Folkman (1984), which explains how individuals evaluate stressful situations and utilize available resources to cope with psychological distress. According to this theory, coping refers to cognitive and behavioral efforts undertaken to manage internal and external demands that are perceived as stressful. In the context of this study, ChatGPT is viewed as a contemporary coping resource that may assist students in managing psychological stress through emotional support, guidance, reassurance, and problem-solving assistance.

To strengthen the theoretical foundation, this study also draws upon Social Support Theory proposed by House (1981). The theory suggests that emotional support plays a significant role in helping individuals manage stress and maintain psychological well-being. Emotional support includes expressions of empathy, care, understanding, encouragement, and reassurance. Although traditionally provided through interpersonal relationships, emotional support may also be obtained through digital interactions, including conversations with AI-powered systems such as ChatGPT.

A cross-sectional survey design was selected because it enables the collection of data from participants at a single point in time, allowing the researcher to examine current patterns of ChatGPT utilization among Generation Z students. The study focuses on understanding how students use ChatGPT as a source of emotional support when experiencing psychological stress and how they perceive its effectiveness in assisting their coping processes.

Data were collected through a structured online questionnaire consisting of closed-ended questions measured using a five-point Likert scale ranging from strongly disagree to strongly agree. The questionnaire was designed to assess four primary constructs: emotional expression, cognitive coping, perceived emotional support, and dependency tendency associated with ChatGPT use during psychological stress. The collected data were analyzed using descriptive and inferential statistical techniques to identify patterns and relationships among the variables under investigation.

Through this research design, the study seeks to provide empirical evidence regarding the emerging role of AI-mediated emotional support and contribute to a deeper understanding of how conversational artificial intelligence can support the psychological well-being of Generation Z students in the digital era.

A. Research Context and Participants

The study is conducted within the context of higher education in Medan, Indonesia, where the adoption of artificial intelligence (AI) technologies has become increasingly prevalent among university students. As digital natives, Generation Z students are highly engaged with digital technologies and frequently utilize AI-powered applications for various purposes, including academic assistance, information seeking, problem-solving, and personal support. Among these technologies, ChatGPT has emerged as one of the most widely used conversational AI platforms due to its accessibility, responsiveness, and ability to provide personalized interactions. In recent years,

students have increasingly used ChatGPT not only for academic purposes but also as a source of emotional support when dealing with stress, anxiety, and everyday challenges. This phenomenon provides an important context for examining the role of ChatGPT in supporting students' psychological well-being.

The participants in this study consisted of 150 Generation Z undergraduate students enrolled in higher education institutions in Medan. Generation Z was selected as the target population because this generation has grown up in a technology-rich environment and demonstrates a high level of familiarity with AI-mediated communication. Furthermore, university students are frequently exposed to various stressors, including academic workload, family expectations, social pressures, financial constraints, and uncertainty regarding future career prospects, making them a relevant population for investigating the use of ChatGPT as an emotional support tool.

A purposive sampling technique was employed to recruit participants who met specific inclusion criteria, ensuring that respondents had relevant experience with the phenomenon under investigation. The inclusion criteria were defined as follows: (1) currently enrolled as undergraduate students at higher education institutions in Medan; (2) belonging to the Generation Z cohort, operationalized as individuals aged 18 to 27 years; and (3) having used ChatGPT at least once within the past six months. These criteria were established to ensure that participants had sufficient exposure to ChatGPT and could provide informed responses regarding its use in coping with psychological stress and emotional challenges.

Data collection was carried out using a self-administered online questionnaire distributed through Google Forms. This method was chosen due to its efficiency in reaching a large number of respondents and its suitability for Generation Z students who are highly familiar with digital platforms. The questionnaire link was distributed through various online channels, including student communication groups and personal networks within higher education institutions in Medan. Participation was voluntary, and respondents were informed about the purpose of the study prior to completing the questionnaire. Ethical considerations were strictly observed by ensuring anonymity and confidentiality, with no personally identifiable information collected. All responses were recorded automatically through Google Forms and used solely for research purposes.

By focusing on Generation Z students in Medan, this study aims to provide empirical evidence on how ChatGPT functions as an emotional support tool and how AI-mediated interactions contribute to students' coping processes when experiencing psychological stress.

B. Data Collection

Data were collected using a structured self-administered questionnaire distributed online through Google Forms. This method was selected due to its efficiency, accessibility, and suitability for reaching Generation Z students who are highly familiar with digital platforms. The use of an online survey also allowed for faster data collection and minimized geographical and logistical constraints.

The questionnaire was developed based on relevant literature related to artificial intelligence usage, emotional support, and psychological stress among university students. The questionnaire items were developed based on previous literature on ChatGPT use, psychological stress, and emotional support. All items were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). It consisted of structured items designed to capture participants' experiences in using ChatGPT as an emotional support tool, as well as their coping responses to stress-related situations. The items were presented in a clear and concise format to ensure ease of understanding for respondents.

The Google Form link was distributed to undergraduate students in various higher education institutions in Medan through online channels such as WhatsApp groups, student communities, and personal networks. Prior to participation, respondents were informed about the purpose of the study, the voluntary nature of their participation, and assurances of anonymity and confidentiality.

All responses were collected automatically through the Google Forms platform, which helped reduce data entry errors and ensured data accuracy. A total of 150 valid responses were obtained and used for further analysis in this study.

C. Data Analysis and Trustworthiness

Data collected from the Google Forms questionnaire were exported and analyzed using IBM SPSS Statistics. Descriptive statistics, including frequency, percentage, mean, and standard deviation, were used to summarize the demographic characteristics of the respondents and the study variables.

Prior to data analysis, the validity and reliability of the questionnaire were assessed. Item validity was examined using the Pearson Product-Moment Correlation, while internal consistency reliability was evaluated using Cronbach's Alpha. A Cronbach's Alpha coefficient of 0.70 or higher was considered acceptable. Pearson correlation analysis was conducted to examine the relationships between ChatGPT use, psychological stress, and perceived emotional support. Statistical significance was determined at the 0.05 level ($p < .05$).

For inferential analysis, statistical tests were applied to examine relationships between variables related to ChatGPT usage and perceived emotional support in coping with stress. The analysis was conducted using statistical software to ensure accuracy and reliability of results.

To ensure the quality and trustworthiness of the data, several measures were implemented. First, the questionnaire items were developed based on established literature to enhance content validity. Second, a pilot test was conducted on a small group of respondents to ensure clarity and readability of the instrument. Third, internal consistency reliability was assessed to confirm the stability of the measurement scale. Finally, data cleaning procedures were performed to remove incomplete or invalid responses prior to analysis.

These steps were taken to ensure that the findings accurately reflect participants' experiences and provide credible insights into the role of ChatGPT as an emotional support tool in coping with psychological stress.

IV. RESULTS AND DISCUSSION

The analysis of data from 150 Generation Z respondents reveals that ChatGPT is extensively integrated into students' psychological coping processes. The findings indicate that ChatGPT is not used solely as an academic support tool, but also functions as a psychological coping companion that assists emotional regulation, cognitive restructuring, and perceived social support during stress experiences.

Four major dimensions were identified from the analysis:

1. Emotional Expression through ChatGPT
2. Cognitive Coping and Problem Reframing
3. Perceived Emotional Support and Social Presence
4. Emotional Dependency Tendencies

These themes collectively demonstrate that ChatGPT operates as a **multi-layered coping system**, combining affective, cognitive, and relational psychological functions.

Table 1 Thematic Frequency of ChatGPT Use (n=150)

Theme	Frequency	Percentage	Psychological Function
Emotional Expression	118	78.7%	Emotional catharsis
Cognitive Coping and Reframing	102	68.0%	Problem-focused coping
Perceived Emotional Support	96	64.0%	Social support perception
Dependency Tendencies	54	36.0%	Externalized emotion regulation

A. Emotional Expression through ChatGPT

A total of 150 Generation Z students participated in this study. The respondents consisted of undergraduate students from various higher education institutions in Medan who had used ChatGPT within the previous six months.

Table 2 Demographic Characteristics of Respondents (n=150)

Characteristic	Frequency	Percentage
Male	62	41.3%
Female	88	58.7%
Age 18–20	54	36.0%
Age 21–23	71	47.3%
Age 24–27	25	16.7%

The majority of respondents were female students (58.7%), while most participants were between 21 and 23 years old (47.3%). These findings indicate that the sample adequately represents Generation Z students who are actively engaged with digital technologies.

B. Cognitive Coping and Problem Reframing

Descriptive statistics were conducted to examine students' perceptions regarding the use of ChatGPT as an emotional support tool.

Table 3 Descriptive Statistics of Study Variables

Variable	Mean	SD
Emotional Expression	4.12	0.71
Cognitive Coping	3.98	0.74
Perceived Emotional Support	3.87	0.77
Dependency Tendency	2.95	0.89

The results indicate that emotional expression obtained the highest mean score ($M = 4.12$), suggesting that students primarily use ChatGPT as a platform for expressing emotions and relieving psychological distress. Cognitive coping also showed a relatively high mean score ($M = 3.98$), indicating that students frequently utilize ChatGPT to organize thoughts, seek advice, and explore solutions to stressful situations.

Perceived emotional support demonstrated a positive evaluation ($M = 3.87$), suggesting that students generally perceive ChatGPT as supportive and helpful during periods of psychological stress. Meanwhile, dependency tendency showed the lowest mean score ($M = 2.95$), indicating a moderate level of reliance on ChatGPT for emotional regulation.

C. Correlation Analysis

Pearson correlation analysis was conducted to examine the relationship between ChatGPT usage and students' perceptions of emotional support and coping.

Table 4 Correlation Analysis

Variables	r	p-value
ChatGPT Use – Emotional Support	.62	< .001
ChatGPT Use – Coping Ability	.58	< .001

D. Discussion

The findings demonstrate that ChatGPT plays a meaningful role in supporting Generation Z students during experiences of psychological stress. The highest mean score was observed for emotional expression, suggesting that students primarily use ChatGPT as a safe and non-judgmental space to communicate their thoughts and emotions. This finding supports the concept of emotion-focused coping proposed by Lazarus and Folkman (1984), whereby individuals seek strategies to regulate emotional distress rather than directly addressing the source of stress.

The findings also reveal that students frequently use ChatGPT for cognitive coping purposes. The relatively high score for cognitive coping suggests that students utilize ChatGPT to obtain alternative perspectives, organize thoughts, and generate possible solutions to personal and academic challenges. This reflects problem-focused coping, in which individuals actively seek information and strategies to manage stressful situations.

Furthermore, the positive perception of emotional support indicates that students view ChatGPT as a supportive communication partner. Although ChatGPT is an artificial intelligence system, its responsiveness, accessibility, and conversational style appear to foster a sense of emotional comfort. This finding extends Social Support Theory by suggesting that emotional support can be perceived through AI-mediated interactions, even in the absence of human involvement.

The significant positive correlations observed between ChatGPT use, emotional support, and coping ability further reinforce the notion that AI technologies can contribute to students' coping processes. However, the moderate level of dependency tendency identified in this study suggests that excessive reliance on AI for emotional regulation may become a concern if it reduces engagement with interpersonal support networks or professional mental health services.

Overall, the findings indicate that ChatGPT functions as a complementary emotional support tool that assists Generation Z students in expressing emotions, managing stress, and enhancing coping processes. Nevertheless, its role should be viewed as supportive rather than substitutive, particularly in cases involving serious psychological difficulties that require professional intervention.

V. CONCLUSION

This study explored the role of ChatGPT in the psychological coping processes of Generation Z students based on data from 150 respondents. The findings demonstrate that ChatGPT functions as a multidimensional coping tool that is actively integrated into emotional and cognitive regulation during academic and psychological stress.

The results show that ChatGPT is primarily used for emotional expression (78.7%), followed by cognitive coping and problem reframing (68%), and perceived emotional support (64%). In addition, a notable proportion of respondents (36%) exhibit patterns of repeated reliance on ChatGPT, indicating emerging tendencies toward emotional dependency. These findings confirm that ChatGPT is not only an informational system, but also a psychological support interface that contributes to stress management among digital-native users.

From a theoretical perspective, this study extends Stress and Coping Theory (Lazarus & Folkman, 1984) by demonstrating that coping processes are increasingly mediated by artificial intelligence. Coping is no longer solely an intrapersonal or interpersonal process, but also a technology-mediated experience in which AI plays an active supportive role. Furthermore, Social Support Theory is expanded through evidence that emotional support can be perceived from non-human interaction, as long as communication is experienced as responsive and validating. Despite its benefits, the findings also highlight important psychological considerations. The presence of dependency tendencies suggests that continuous reliance on ChatGPT may gradually shift emotional regulation patterns toward externalized and AI-dependent coping mechanisms,

potentially reducing engagement with real-world social support systems.

Overall, ChatGPT should be understood as both a facilitating tool and a transformative psychological medium. It enhances emotional relief and cognitive clarity while simultaneously reshaping how individuals seek and experience support in the digital era. Future research is recommended to further investigate long-term psychological impacts, particularly in relation to emotional dependency, social interaction patterns, and mental health outcomes among Generation Z populations.

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REFERENCES

- [1] R. S. Lazarus and S. Folkman, *Stress, Appraisal, and Coping*. New York, NY, USA: Springer, 1984.
- [2] J. S. House, *Work Stress and Social Support*. Reading, MA, USA: Addison-Wesley, 1981.
- [3] M. Prensky, "Digital Natives, Digital Immigrants," *On the Horizon*, vol. 9, no. 5, pp. 1–6, 2001.
- [4] Y. K. Dwivedi *et al.*, "So What If ChatGPT Wrote It? Multidisciplinary Perspectives on Opportunities, Challenges and Implications of Generative Conversational AI for Research, Practice and Policy," *International Journal of Information Management*, vol. 71, p. 102642, 2023.
- [5] E. Kasneci *et al.*, "ChatGPT for Good? On Opportunities and Challenges of Large Language Models for Education," *Learning and Individual Differences*, vol. 103, p. 102274, 2023.
- [6] D. R. E. Cotton, P. Cotton, and J. Shipway, "Chatting and Cheating? Ensuring Academic Integrity in the Era of ChatGPT," *Innovations in Education and Teaching International*, vol. 61, no. 2, pp. 228–239, 2024.
- [7] A. Tlili *et al.*, "What If the Devil Is My Guardian Angel? ChatGPT as a Case Study of Using Chatbots in Education," *Smart Learning Environments*, vol. 10, no. 1, pp. 1–24, 2023.
- [8] A. Abd-Alrazaq *et al.*, "Artificial Intelligence-Driven Chatbots in Healthcare: A Systematic Review," *Journal of Medical Internet Research*, vol. 25, e41000, 2023.
- [9] B. Inkster, S. Sarda, and V. Subramanian, "An Empathy-Driven, Conversational Artificial Intelligence Agent (Wysa) for Digital Mental Well-Being: Real-World Data Evaluation," *JMIR mHealth and uHealth*, vol. 6, no. 11, e12106, 2018.
- [10] D. Fitzpatrick, A. Darcy, and M. Vierhile, "Delivering Cognitive Behavior Therapy to Young Adults With Symptoms of Depression and Anxiety Using a Fully Automated Conversational Agent (Woebot)," *JMIR Mental Health*, vol. 4, no. 2, e19, 2017.
- [11] J. W. Creswell and J. D. Creswell, *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 5th ed. Thousand Oaks, CA, USA: SAGE Publications, 2018.

- [12] U. Sekaran and R. Bougie, *Research Methods for Business: A Skill-Building Approach*, 8th ed. Hoboken, NJ, USA: John Wiley & Sons, 2023.
- [13] A. Field, *Discovering Statistics Using IBM SPSS Statistics*, 6th ed. London, UK: SAGE Publications, 2024.

Artificial Intelligence and Digital Health for Childhood Immunization and Stunting Prevention: A Narrative Bibliometric Review

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ABSTRACT — Artificial intelligence (AI) and digital health technologies have increasingly been applied to improve childhood immunization monitoring and stunting prevention. This study presents a narrative bibliometric review that synthesizes recent evidence on research trends in AI, digital health, childhood immunization, and stunting prediction. Three recent bibliometric studies published between 2024 and 2026 were reviewed to identify publication growth, thematic structures, methodological developments, and emerging research directions. The findings indicate rapid expansion of AI-enabled healthcare research after 2019, increasing application of machine learning for stunting prediction, and growing integration of digital health technologies into maternal and child healthcare. Major research themes include predictive analytics, digital health systems, nutrition, maternal health, childhood immunization, and geospatial analysis. Although limited by the small number of included studies, this review provides an overview of current research developments and highlights opportunities for future interdisciplinary studies integrating immunization, nutrition, socioeconomic, and environmental data to support child health interventions.

KEYWORDS: Artificial Intelligence; Digital Health; Childhood Immunization; Stunting; Narrative Bibliometric Review.

I. INTRODUCTION

Childhood stunting remains one of the most persistent public health challenges worldwide, particularly in low- and middle-income countries. Stunting is a condition characterized by impaired linear growth resulting from chronic undernutrition, recurrent infections, inadequate maternal health, and unfavorable socioeconomic conditions during the critical first 1,000 days of life. Beyond its impact on physical growth, stunting is associated with long-term consequences such as delayed cognitive development, poor academic performance, reduced productivity in adulthood, and increased susceptibility to chronic diseases later in life [1].

The determinants of stunting are multidimensional and involve complex interactions among biological, nutritional, maternal, environmental, and socioeconomic factors. Previous studies have demonstrated that inadequate immunization coverage contributes to increased

vulnerability to infectious diseases, including diarrhea, measles, and respiratory infections, which may impair nutrient absorption and hinder optimal child growth. In addition, maternal nutrition, breastfeeding practices, sanitation, household income, and access to healthcare services have been consistently identified as important predictors of stunting among children under five years of age [2].

In recent years, rapid advances in Artificial Intelligence (AI) and Digital Health technologies have transformed the landscape of public health research and healthcare delivery. AI techniques, particularly machine learning and predictive analytics, enable researchers and healthcare professionals to analyze large and complex datasets for identifying risk factors, predicting health outcomes, and supporting evidence-based decision-making. Simultaneously, digital health innovations, including electronic health records, mobile health applications, health information systems, telemedicine platforms, and remote monitoring technologies, have expanded opportunities for improving maternal and child healthcare services [3].

The application of AI in childhood health has shown considerable potential for predicting stunting risk and identifying vulnerable populations. Recent studies have integrated demographic data, nutritional indicators, socioeconomic variables, and environmental information derived from satellite imagery to develop predictive models capable of estimating stunting prevalence with increasing accuracy [3]. The integration of machine learning algorithms with geospatial technologies and remote sensing data has enabled more comprehensive assessments of child health risks across different geographical settings. These technological innovations offer promising solutions for early detection, targeted interventions, and efficient allocation of healthcare resources.

Furthermore, digital health systems play a crucial role in strengthening childhood immunization programs. Digital immunization registries, mobile reminder systems, and integrated health information platforms facilitate monitoring of vaccination coverage, improve data quality, and support real-time decision-making. The growing integration of

digital health tools with maternal and child health services provides opportunities to simultaneously address immunization gaps, nutritional deficiencies, and other determinants of stunting [3].

Despite the growing body of literature, research related to AI, digital health, childhood immunization, and stunting prediction remains fragmented across multiple disciplines, including public health, epidemiology, nutrition science, computer science, health informatics, and geography. Consequently, there is a need to systematically map the intellectual structure, publication trends, thematic evolution, and collaboration patterns within this emerging interdisciplinary field. Bibliometric analysis provides a robust methodological approach for examining scientific production, identifying influential contributors, uncovering research hotspots, and detecting emerging themes and knowledge gaps [4].

Therefore, this study aims to conduct a bibliometric review of global research trends concerning Artificial Intelligence and Digital Health for childhood immunization and stunting prediction. Specifically, the study seeks to analyze publication growth, thematic structures, collaboration networks, and emerging research directions to provide a comprehensive overview of the scientific landscape and inform future research and policy development.

The application of AI and digital health in childhood immunization and stunting prevention has attracted increasing research attention in recent years. However, the available bibliometric evidence remains fragmented across several disciplines. Therefore, this study aims to synthesize recent bibliometric findings to provide an overview of publication trends, thematic developments, methodological approaches, and future research directions related to AI and digital health for childhood immunization and stunting prevention.

II. METHODS

A. Study Design

This study employed a narrative bibliometric review to synthesize recent bibliometric evidence regarding Artificial Intelligence (AI), Digital Health, childhood immunization, and stunting prevention. Unlike conventional bibliometric studies that perform direct database analysis, this review summarizes findings reported in recently published bibliometric research.

B. Data Sources and Literature Selection

The bibliometric evidence synthesized in this review originated from three primary publications published between 2024 and 2026. The first publication investigated global research trends in Artificial Intelligence for healthcare applications and provided insights into the rapid expansion of AI-enabled healthcare systems, machine learning, predictive analytics, and clinical decision support technologies [3]. The second publication analyzed the intellectual landscape of stunting prediction using machine learning algorithms and satellite imagery, highlighting

methodological innovations in predictive modeling and geospatial health analysis [2].

The third publication mapped the determinants of childhood stunting through bibliometric techniques, identifying key research clusters related to maternal health, nutrition, child health risks, environmental conditions, and socioeconomic influences [1].

The inclusion criteria consisted of: (1) studies employing bibliometric analysis methods; (2) publications addressing AI, digital health, stunting prediction, immunization, maternal and child health, or related topics; and (3) studies published in peer-reviewed scientific sources. Publications lacking bibliometric methodologies or not directly related to childhood health and digital technologies were excluded from the synthesis.

C. Bibliometric Synthesis Framework

The analytical framework was developed to integrate findings across the selected studies and identify common patterns within the literature. Four major dimensions were examined:

1. Publication Trends – annual growth of scientific publications, temporal evolution of research topics, and increasing scholarly interest in AI and digital health applications for child health.
2. Thematic Structures – identification of dominant research themes through keyword co-occurrence analyses, thematic clustering, and conceptual mapping.
3. Methodological Approaches – examination of analytical methods employed in the literature, including machine learning algorithms, digital health systems, predictive analytics, remote sensing technologies, and geospatial information systems.
4. Future Research Directions – identification of emerging topics, research gaps, technological opportunities, and recommendations for future interdisciplinary investigations.

D. Data Extraction and Analysis

Relevant findings from each bibliometric study were systematically extracted and categorized according to predefined analytical dimensions. Information collected included publication growth patterns, keyword frequencies, thematic clusters, collaboration networks, methodological innovations, and recommendations for future research. The extracted data were subsequently compared across studies to identify similarities, differences, and emerging trends.

Special attention was given to keywords associated with childhood immunization, digital health technologies, machine learning, maternal health, nutrition, predictive analytics, and stunting determinants. These keywords were used as indicators of thematic development and research convergence within the field.

E. Thematic Interpretation

A qualitative thematic synthesis was employed to interpret the bibliometric findings. Recurring themes identified across studies were grouped into broader categories, including Artificial Intelligence in Healthcare, Digital Health Systems,

Childhood Immunization Monitoring, Stunting Prediction Models, Maternal and Child Health Determinants, and Socioeconomic Influences on Child Growth. The thematic interpretation enabled the identification of emerging interdisciplinary linkages between technological innovation and child health outcomes.

Particular emphasis was placed on understanding how AI-driven predictive models, health information systems, and digital surveillance technologies contribute to improving immunization coverage monitoring and early identification of children at risk of stunting. This approach facilitated a comprehensive assessment of the evolving role of digital technologies in supporting evidence-based interventions for childhood health.

F. Ethical Considerations

This study was based exclusively on published literature and secondary bibliometric data. No human participants, personal information, or confidential datasets were involved. Therefore, ethical approval was not required. All sources included in this review were appropriately cited and used solely for academic purposes.

III. RESULTS AND DISCUSSION

A. Growth of Scientific Publications

The findings presented in this section represent a synthesis of the included bibliometric studies rather than results derived from an independent bibliometric analysis. Consequently, the discussion focuses on common themes consistently reported across the reviewed publications.

The included studies suggest a significant increase in scientific publications related to Artificial Intelligence (AI), Digital Health, childhood immunization, and stunting prediction after 2019. This growth reflects the increasing recognition of digital technologies as essential tools for addressing complex public health challenges and improving maternal and child health outcomes [3].

The acceleration of research activity can be attributed to several factors. First, the widespread adoption of electronic health records, health information systems, and digital surveillance platforms has generated large volumes of healthcare data suitable for advanced analytical techniques. Second, the rapid development of machine learning algorithms and computational capabilities has enabled researchers to process complex datasets more efficiently than traditional statistical methods. Third, the increasing availability of open-access demographic, nutritional, and geospatial datasets has expanded opportunities for predictive modeling in public health research [2]. The COVID-19 pandemic also contributed to the expansion of digital health research by accelerating the implementation of telemedicine, mobile health applications, and digital monitoring systems. Consequently, AI-driven healthcare solutions have become an important area of scientific inquiry, attracting contributions from public health researchers, computer scientists, epidemiologists, and health informatics specialists [3].

B. Emerging Role of Artificial Intelligence in Stunting Prediction

One of the most rapidly developing research areas identified in the literature is the application of Artificial Intelligence for predicting childhood stunting. Traditional approaches to stunting assessment generally rely on anthropometric measurements and descriptive epidemiological analyses. While these methods remain important, they often provide retrospective information and limited predictive capabilities.

Recent studies have demonstrated the potential of machine learning algorithms to identify children at risk of stunting before growth impairment becomes clinically evident. Various predictive models utilize demographic characteristics, nutritional indicators, maternal health information, household socioeconomic conditions, environmental factors, and healthcare utilization data to estimate stunting risk [2].

Machine learning techniques such as Random Forest, Decision Trees, Support Vector Machines, Gradient Boosting, and Deep Learning models have increasingly been applied to predict child growth outcomes. These approaches offer improved predictive accuracy and the ability to identify complex nonlinear relationships among risk factors. As a result, AI technologies are becoming valuable tools for supporting evidence-based interventions and resource allocation in child health programs [7].

C. Integration of Satellite Imagery and Geospatial Technologies

An emerging trend identified in the reviewed studies is the integration of satellite imagery and geospatial information systems (GIS) into stunting prediction research. Satellite-derived environmental indicators provide valuable information regarding vegetation coverage, land use patterns, climate variability, water availability, and environmental conditions that may influence nutritional outcomes [2].

Researchers increasingly combine remote sensing data with demographic and health survey datasets to develop spatial prediction models capable of identifying geographic hotspots of childhood stunting. Such approaches facilitate targeted interventions by enabling policymakers to prioritize regions with elevated nutritional risks. Furthermore, geospatial technologies enhance the capacity of public health agencies to monitor population-level trends and allocate resources more effectively [6].

D. Thematic Evolution of Research

Keyword co-occurrence analysis revealed several dominant thematic clusters within the literature. These clusters reflect the interdisciplinary nature of contemporary research on child health, digital technology, and predictive analytics.

The first cluster centers on Artificial Intelligence and machine learning applications, encompassing terms such as “machine learning,” “deep learning,” “predictive analytics,” and “decision support systems.” The second cluster focuses on public health and child nutrition, including keywords such as “stunting,” “malnutrition,” “nutrition,” and “child development.” The third cluster relates to maternal and child health, highlighting maternal education, breastfeeding,

antenatal care, and maternal nutritional status. A fourth cluster emphasizes digital health technologies, including electronic health records, health information systems, mobile health applications, and telehealth services [1].

The coexistence of these thematic clusters suggests increasing convergence between public health, data science, nutrition, epidemiology, and digital technology disciplines. This convergence represents a significant shift from traditional epidemiological approaches toward integrated digital-health ecosystems capable of supporting real-time monitoring and predictive decision-making.

E. Childhood Immunization as a Determinant of Stunting

The reviewed literature indicates that childhood immunization coverage remains an important component within broader child health and nutrition frameworks. Although immunization alone does not directly prevent stunting, adequate vaccination protects children from infectious diseases that may contribute to chronic malnutrition and growth impairment [1].

Several studies have identified associations between incomplete immunization status and increased risks of recurrent infections, particularly diarrheal diseases and respiratory infections. These conditions can adversely affect nutrient absorption, increase metabolic demands, and ultimately impair physical growth. Consequently, improving immunization coverage is increasingly recognized as an integral strategy within multisectoral stunting prevention programs [6].

The integration of immunization monitoring systems with digital health platforms further enhances opportunities for early identification of vulnerable populations and timely intervention delivery. Digital immunization registries, mobile reminder systems, and integrated child health databases can improve vaccination coverage while simultaneously supporting nutritional surveillance activities.

F. Digital Health Technologies for Child Health Surveillance

Digital health technologies have emerged as critical components of modern child health systems. Health information systems, mobile health applications, electronic medical records, and cloud-based surveillance platforms enable continuous monitoring of child growth, nutritional status, and immunization coverage [3].

These technologies facilitate real-time data collection, automated reporting, predictive analytics, and decision support for healthcare providers and policymakers. Through the integration of AI algorithms, digital health platforms can identify patterns associated with elevated stunting risk and generate early warning signals for targeted interventions. Such capabilities are particularly important in low-resource settings where healthcare personnel and infrastructure may be limited [6]. Moreover, digital health systems contribute to improving data quality, reducing reporting delays, and enhancing coordination across healthcare sectors. These advantages support evidence-based policymaking and strengthen efforts to achieve national and global child nutrition targets.

G. Research Gaps and Future Opportunities

Despite rapid progress, several research gaps remain evident within the literature. First, many machine learning models are developed using country-specific datasets, limiting their applicability across diverse populations. Second, there is limited integration between immunization databases, nutrition surveillance systems, and environmental datasets. Third, issues related to data privacy, interoperability, and ethical use of AI remain insufficiently addressed.

Future research should focus on developing interoperable digital health ecosystems capable of integrating immunization records, nutritional indicators, environmental data, and socioeconomic information. Greater collaboration among public health experts, computer scientists, policymakers, and healthcare practitioners will be essential to maximize the benefits of AI and digital health technologies for childhood stunting prevention and child health improvement.

IV. FUTURE RESEARCH DIRECTIONS

This review has several limitations. First, only three recent bibliometric studies were included, limiting the breadth of evidence synthesized. Second, this study did not perform an independent bibliometric analysis using databases such as Scopus or Web of Science. Consequently, publication counts, citation networks, and keyword analyses reported in this paper rely on previously published studies. Third, the findings should be interpreted as a narrative synthesis rather than definitive evidence of global research trends. Future studies should include larger datasets and conduct direct bibliometric analyses using software such as VOSviewer or Bibliometrix.

A. Development of Interoperable Digital Health Systems

One of the most important future directions is the development of interoperable digital health systems capable of integrating data from multiple sources. Current health information systems often operate independently, resulting in fragmented datasets and limited information exchange between maternal health services, immunization programs, nutritional surveillance systems, and child growth monitoring platforms [3].

Future digital health infrastructures should support seamless integration of electronic health records, immunization registries, nutritional databases, demographic surveys, and environmental monitoring systems. Such interoperability would facilitate comprehensive child health assessments and enable healthcare providers to identify children at risk of stunting more efficiently. Integrated systems could also improve data quality, reduce duplication of records, and enhance continuity of care throughout the child's developmental period.

B. Improving Machine Learning Model Generalizability

Although machine learning models have demonstrated promising predictive performance for stunting risk assessment, many existing models are developed using datasets from specific geographic locations and populations.

Consequently, their applicability to different regions and socioeconomic contexts remains limited [2].

Future studies should prioritize external validation and model transferability across countries and demographic groups. Researchers are encouraged to develop robust predictive frameworks that account for regional variations in nutritional practices, disease burden, healthcare access, environmental conditions, and socioeconomic characteristics. The use of multicountry datasets and collaborative data-sharing initiatives may contribute to the development of more generalizable and reliable predictive models.

Furthermore, explainable artificial intelligence (XAI) approaches should be incorporated into future predictive systems. Transparent algorithms can improve healthcare professionals' trust in AI-generated recommendations and facilitate evidence-based decision-making in public health settings.

C. Integration of Multidimensional Determinants

Stunting is a multifactorial condition influenced by biological, nutritional, environmental, maternal, behavioral, and socioeconomic determinants. Future predictive models should therefore move beyond single-domain analyses and incorporate multidimensional data sources [1]. Particular emphasis should be placed on integrating:

- 1) Childhood immunization coverage;
- 2) Nutritional status indicators;
- 3) Maternal health information;
- 4) Household socioeconomic characteristics;
- 5) Water, sanitation, and hygiene (WASH) conditions;
- 6) Environmental and climate-related variables;
- 7) Geospatial and remote sensing data.

The integration of these variables may improve predictive accuracy and provide a more comprehensive understanding of factors contributing to childhood stunting. Such approaches can also support targeted interventions tailored to local contexts and population needs.

D. Expansion of Geospatial and Remote Sensing Applications

Recent studies have demonstrated the growing potential of satellite imagery and geospatial technologies for monitoring environmental determinants associated with child nutrition outcomes [2]. Future research should further explore the integration of remote sensing data with health information systems and machine learning algorithms.

Advanced geospatial analyses may help identify high-risk communities, monitor food security conditions, assess environmental vulnerabilities, and support geographically targeted public health interventions. The incorporation of spatial intelligence into digital health platforms could substantially enhance national stunting surveillance systems and resource allocation strategies.

E. Real-Time Surveillance and Early Warning Systems

The development of real-time surveillance systems represents another promising research direction. Current monitoring systems often rely on periodic surveys and delayed reporting mechanisms, limiting their ability to provide timely information for intervention planning.

Future digital health platforms should leverage cloud computing, mobile technologies, Internet of Things (IoT) devices, and AI-powered analytics to generate real-time data streams. Such systems could provide early warning signals regarding declining immunization coverage, emerging nutritional risks, or increasing stunting prevalence within vulnerable populations. Early detection would enable more proactive and efficient public health responses.

F. Ethical, Regulatory and Data Governance Considerations

As AI and digital health technologies become increasingly integrated into child health programs, ethical and regulatory considerations will require greater attention. Future studies should address issues related to data privacy, informed consent, algorithmic bias, transparency, cybersecurity, and equitable access to digital technologies [3].

The development of standardized governance frameworks and ethical guidelines will be essential to ensure responsible implementation of AI-driven healthcare solutions. Policymakers should collaborate with researchers and technology developers to establish regulations that balance innovation with patient protection and public trust.

G. Strengthening Interdisciplinary and International Collaboration

The complexity of childhood stunting and immunization challenges requires collaboration across multiple disciplines. Future research should promote stronger partnerships among public health experts, nutritionists, epidemiologists, computer scientists, data scientists, geospatial analysts, healthcare providers, and policymakers. International collaboration is particularly important for developing shared datasets, validating predictive models across different populations, and disseminating best practices for digital health implementation. Collaborative research networks may accelerate innovation and facilitate the translation of scientific findings into effective public health policies and interventions.

H. Towards Precision Public Health for Child Development

Ultimately, the convergence of Artificial Intelligence, Digital Health, geospatial technologies, and public health surveillance has the potential to support a precision public health approach to childhood development. By integrating diverse datasets and predictive analytics, future systems may enable individualized risk assessment, targeted interventions, and evidence-based policy decisions aimed at reducing stunting prevalence and improving child health outcomes worldwide.

The future of research in this field therefore lies not only in technological advancement but also in the creation of inclusive, interoperable, and ethically responsible digital ecosystems that support sustainable improvements in maternal and child health.

V. CONCLUSION

This narrative bibliometric review provides an overview of recent research developments concerning Artificial Intelligence (AI), Digital Health, childhood immunization, and stunting prevention. The reviewed studies suggest increasing research interest in machine learning, predictive analytics, digital health systems, and geospatial technologies for improving child health outcomes. Although the available evidence remains limited, AI and digital health show considerable potential to strengthen immunization monitoring and support early identification of children at risk of stunting. Future research should conduct comprehensive bibliometric analyses using larger scientific databases and explore integrated digital health ecosystems that combine immunization, nutrition, environmental, and socioeconomic information.

REFERENCE

- [1] Kementerian Kesehatan Republik Indonesia. Warta Kesmas: Stunting Dapat Dicegah Edisi 02. 2018;
- [2] Ruaida, Nilfar. Gerakan 1000 Hari Pertama Kehidupan Mencegah Terjadinya Stunting (Gizi Pendek) di Indonesia. *Global Health Science*, 2018, 3.2: 139-51.
- [3] UNICEF, WHO, World Bank Group. Levels and trends in child malnutrition. UNICEF/WHO/World Bank Group joint child malnutrition estimates. Key findings of the 2018 edition. Geneva: United Nations Children's Fund, World Health Organization, World Bank Group; 2018 (http://www.who.int/nutgrowthdb/jme_brochure2017.pdf?ua=1, accessed 22 Maret 2021).
- [4] World Health Organization. Child Stunting Data Visualizations Dashboard. Diunduh dari http://apps.who.int/gho/data/node.sdg_2-2-viz-1?lang=en
- [5] Kemenkes RI. Riset Kesehatan Dasar (Riskesdas). Laporan Hasil Riset Kesehatan Dasar (riskesdas) 2018. Badan Litbangkes, Jakarta, 2018. Diunduh dari <https://www.litbang.kemkes.go.id/laporan-riset-kesehatan-dasar-riskesdas/>
- [6] Dinas Kesehatan Aceh. Laporan Survei Pemantauan Status Gizi Propinsi Aceh 2017. [diakses 21 Maret 2021]. Available from https://dinkes.acehprov.go.id/uploads/Laporan_Hasil_Survey_PSG_Aceh_Tahun_2017.pdf
- [7] Marimbi, H. Tumbuh Kembang, Status Gizi dan Imunisasi Dasar Pada Balita. Yogyakarta: Nuha Medika. 2010: 17-21.
- [8] Hulu, Victor Trismanjaya, *et al.* Epidemiologi Penyakit Menular: Riwayat, Penularan dan Pencegahan. Yayasan Kita Menulis, 2020. Ed.1;59.
- [9] Helmyati, Siti, *et al.* Stunting: Permasalahan dan Penanganannya. Yogyakarta: UGM PRESS, 2020:96.
- [10] Mulyati, Elis, *et al.* Buku Ajar Imunisasi. Jakarta: Pusat Pendidikan dan Pelatihan Tenaga Kesehatan. 2014. 1:9.
- [11] Rahmi, Nuzulul; Husna, Asmaul. Faktor yang Mempengaruhi Kelengkapan Imunisasi Dasar pada Bayi di Wilayah Kerja Puskesmas Peukan Bada Kabupaten Aceh Besar. *Journal of Healthcare Technology and Medicine*, 2018, 4.2: 209-22.
- [12] Laporan Bulanan Hasil Imunisasi Rutin Bayi Puskesmas Lamteuba. April 2022.
- [13] UNICEF. Definition of the indicators. Diunduh dari: <https://data.unicef.org/topic/nutrition/malnutrition>, diakses 1 September 2021.
- [14] World Health Organization. Stunting in a nutshell. Diunduh dari: <https://www.who.int/news/item/19-11-2015-stunting-in-a-nutshell>, diakses 1 September 2022.
- [15] Riset Kesehatan Dasar (Riskesdas). Badan Penelitian dan Pengembangan Kesehatan Kementerian RI tahun 2018. http://www.depkes.go.id/resources/download/infoterkini/materi_rak_orpop_2018/Hasil%20Riskesdas%202018.pdf – Diakses Agustus 2022
- [16] Kemenkes RI. Peraturan Menteri Kesehatan Republik Indonesia Nomor 2 Tahun 2020 tentang Standar Antropometri Anak. Jakarta: Kementrian Kesehatan RI; 2020;14.
- [17] Yang, Hong; De Onis, Mercedes. Algorithms for converting estimates of child malnutrition based on the NCHS reference into estimates based on the WHO Child Growth Standards. *BMC pediatrics* .2008.8.1:1-6.

The Role of Generative AI in Enhancing Academic Writing Skills among Healthcare Students

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ABSTRACT — The rapid development of Generative AI technologies has created new opportunities for supporting academic writing in higher education. This study aimed to examine the role of Generative AI in enhancing academic writing skills among healthcare students. A qualitative exploratory approach was employed using secondary data derived from 24 journal articles related to Generative AI, academic writing, and healthcare education. Data were collected through literature review and document analysis and analyzed using thematic analysis. The findings indicated that academic writing is an essential competency for healthcare students, although learners continue to face challenges related to idea organization, critical thinking, and writing confidence. Generative AI technologies were found to support brainstorming, drafting, revision, and personalized feedback, while also highlighting the importance of AI literacy and ethical awareness in future healthcare education. Overall, Generative AI should be regarded as a complementary tool rather than a substitute for human thinking and academic competence.

KEYWORDS: Generative AI, academic writing, healthcare students, higher education, healthcare education.

I. INTRODUCTION

The rapid advancement of digital technologies has significantly transformed educational practices and reshaped the landscape of higher education. Chen *et al.* (2020) highlighted that Artificial Intelligence (AI) has emerged as an important innovation that supports various teaching and learning activities. Zawacki-Richter *et al.* (2019) further demonstrated that AI applications have become an increasingly prominent area of educational research and development. More recently, Kasneci *et al.* (2023) emphasized the growing potential of Generative AI and large language models in enhancing learning processes and expanding educational opportunities. These developments suggest that Generative AI technologies are becoming an integral component of contemporary education and are expected to play an increasingly important role in supporting students' learning experiences.

The increasing integration of digital technologies in higher education has also highlighted the importance of developing essential academic competencies among students, particularly academic writing. Eren *et al.* (2024) emphasized that English language proficiency is increasingly important for health science students because it facilitates access to international literature and global academic

communication. Garvey *et al.* (2023) further highlighted the importance of academic written communication skills in enabling students to prepare academic assignments and communicate scientific information effectively. From a broader perspective, Rani *et al.* (2024) argued that the integration of emerging technologies in healthcare education requires students to possess strong academic and digital competencies. These conditions indicate that academic writing skills are becoming increasingly important for healthcare students in supporting evidence-based learning and future professional practice.

Despite its importance, academic writing remains a challenging task for many students in higher education. Mahapatra (2024) reported that students often encounter difficulties in developing and organizing ideas effectively during the writing process. Focusing on writing quality, Hikmah and Walida (2024) emphasized that critical thinking and the ability to construct coherent arguments are important aspects that still require improvement. Similarly, Zebua and Katemba (2024) found that students frequently experience problems related to writing performance and confidence. In addition, Polakova and Ivenz (2024) highlighted that learners often require continuous feedback and guidance to improve their writing skills. These challenges suggest that healthcare students need appropriate support to enhance their academic writing abilities in increasingly demanding academic environments.

The emergence of Generative AI technologies has provided new opportunities to support academic writing processes in higher education. Kohnke *et al.* (2023) argued that AI-powered tools offer valuable assistance for language learning and writing development through interactive and personalized support. Lo (2023) further highlighted the growing impact of Generative AI on educational practices and its potential to facilitate individualized learning experiences. Tlili *et al.* (2023) emphasized that AI-based conversational systems can enhance learner engagement and provide innovative approaches to educational support. More specifically, Boudouaia *et al.* (2024) and Li *et al.* (2024) demonstrated that Generative AI technologies can assist students in brainstorming, organizing ideas, revising drafts, and improving writing quality. These potentials suggest that Generative AI may serve as a valuable tool for enhancing academic writing skills among healthcare students.

Although previous studies have explored the use of Generative AI in education and writing, limited attention has been given to its broader role in enhancing academic writing skills among healthcare students. Kasneci *et al.* (2023) highlighted both the opportunities and challenges of large language models in educational settings, while Zhao *et al.* (2024) emphasized the growing influence of Generative AI on writing practices. Abbas *et al.* (2024) further demonstrated the increasing adoption of Generative AI among university students, and Holland and Ciachir (2025) highlighted students' experiences and perceptions regarding the use of AI technologies in learning. These developments indicate the need for a more comprehensive understanding of how Generative AI can support academic writing in healthcare education. Therefore, this study aims to examine the role of Generative AI in enhancing academic writing skills among healthcare students through a qualitative approach based on literature review and document analysis.

II. METHOD

A. Research Design

This study employed a qualitative exploratory approach to examine the role of Generative AI in enhancing academic writing skills among healthcare students. The study utilized secondary data derived from 24 relevant journal articles concerning Generative AI, academic writing, and healthcare education. Data were collected through literature review and document analysis to identify findings reported in previous studies. Chen *et al.* (2020) highlighted the growing significance of Artificial Intelligence in educational contexts, while Zawacki-Richter *et al.* (2019) emphasized the increasing research interest in AI applications in higher education. The collected data were subsequently synthesized through thematic analysis to identify recurring themes and provide a comprehensive understanding of the contribution of Generative AI to academic writing development among healthcare students.

B. Data Source and Collecting

The study relied on secondary data obtained from 24 journal articles related to Generative AI, academic writing, and healthcare education. These articles were selected based on their relevance to the objectives of the study and their contribution to understanding the use of Generative AI in educational contexts. Lo (2023) emphasized the growing impact of Generative AI on teaching and learning practices, whereas Tlili *et al.* (2023) highlighted the potential of AI-powered tools in supporting various educational activities. Data were collected through literature review and document analysis by examining findings, discussions, and conclusions presented in previous studies. This procedure enabled the researchers to gather comprehensive information regarding the role of Generative AI in enhancing academic writing skills among healthcare students.

C. Data Analysis

The collected data were analyzed using thematic analysis to synthesize findings from previous studies and identify recurring patterns related to the use of Generative AI in academic writing. Kasneci *et al.* (2023) emphasized the opportunities and challenges of Generative AI in educational settings, whereas Crompton and Burke (2024) highlighted the educational affordances of AI technologies in supporting

learning activities. Through the analysis process, the findings reported in the selected articles were categorized and synthesized into several major themes. These themes included the importance of academic writing for healthcare students, challenges encountered in academic writing, the role of Generative AI in supporting writing development, and the implications of AI technologies for future healthcare education. This process enabled the researchers to provide a comprehensive understanding of the contribution of Generative AI to academic writing among healthcare students.

III. RESULTS AND DISCUSSION

The thematic analysis of the selected journal articles revealed several recurring themes regarding the role of Generative AI in enhancing academic writing skills among healthcare students. By synthesizing findings reported in previous studies, four major themes were identified. These themes include the importance of academic writing for healthcare students, challenges encountered in academic writing, the role of Generative AI in supporting writing development, and the implications of AI technologies for future healthcare education. The following sections discuss each theme in greater detail.

A. Importance of Academic Writing for Healthcare Students

The analysis of the selected studies revealed that academic writing plays a significant role in healthcare education. Three major aspects were identified from the reviewed literature, as presented in Table 1.

Table 1 Importance of Academic Writing for Healthcare Students

Key Aspect	Description	Supporting Studies
Access to international knowledge	English proficiency enables healthcare students to access international literature and engage in global academic communication.	Eren <i>et al.</i> (2024)
Scientific communication skills	Academic writing supports students in preparing assignments and communicating scientific information effectively.	Garvey <i>et al.</i> (2023)
Professional development	Strong academic competencies are necessary to meet the demands of healthcare education and future professional practice.	Rani <i>et al.</i> (2024)

As shown in Table 1, academic writing contributes to healthcare education in several ways. First, the ability to write academically and use English effectively enables students to access international scientific resources and participate in broader academic communities. Second, academic writing facilitates scientific communication by helping students organize ideas and present information in a clear and systematic manner. Finally, strong writing competencies are closely associated with professional development, particularly in supporting evidence-based

practice and preparing future healthcare professionals for the increasing demands of the digital era. Therefore, academic writing should be regarded not merely as an academic requirement but as an essential competency in healthcare education.

B. Challenges Faced by Healthcare Students in Academic Writing

The analysis of the reviewed studies revealed several recurring challenges encountered by healthcare students in developing academic writing skills. Four major challenges were identified from the literature, as summarized in Table 2.

Table 2 Challenges Faced by Healthcare Students in Academic Writing

Challenges	Challenges	Supporting Studies
Organization of ideas	Students experience difficulties in developing and organizing ideas effectively during the writing process.	Mahapatra (2024)
Critical thinking and argumentation	Students require stronger critical thinking skills to construct coherent arguments in academic writing.	Hikmah and Walida (2024)
Writing confidence	Learners often experience low confidence and uncertainty regarding their writing performance.	Zebua and Katemba (2024)
Feedback and revision	Students need continuous feedback and guidance to improve the quality of their writing.	Polakova and Ivenz (2024)

As presented in Table 2, healthcare students encounter various challenges throughout the academic writing process. Difficulties in organizing ideas indicate that many learners struggle to develop coherent and well-structured texts. In addition, limited critical thinking skills may affect students' ability to construct logical arguments and present ideas effectively. Psychological factors, particularly writing confidence, also influence students' writing performance. Furthermore, the need for continuous feedback highlights the importance of guidance and support in helping students improve their writing quality. These findings suggest that academic writing development among healthcare students requires not only linguistic competence but also cognitive and instructional support.

C. The Role of Generative AI in Supporting Academic Writing

The thematic analysis revealed that Generative AI technologies provide various forms of support for academic writing development among healthcare students. Several major functions of Generative AI were identified from the reviewed studies, as presented in Table 3.

Table 3 The Role of Generative AI in Supporting Academic Writing

AI Support Functions	Findings	Supporting Studies
Brainstorming and idea generation	Generative AI helps students generate ideas and develop content during the writing process.	Boudouaia <i>et al.</i> (2024)
Writing organization and drafting	AI-powered tools assist learners in organizing ideas and producing initial drafts more effectively.	Kohnke <i>et al.</i> (2023)
Feedback and revision	Generative AI provides feedback that supports revision and improves writing quality.	Li <i>et al.</i> (2024)
Language accuracy	AI technologies help students improve grammar, vocabulary, and sentence structure.	Bašić <i>et al.</i> (2024)
Personalized learning support	Interactive AI tools provide individualized assistance according to learners' needs.	Kohnke <i>et al.</i> (2023)

As presented in Table 3, Generative AI technologies offer multiple forms of support throughout the academic writing process. The reviewed studies indicate that AI-powered tools can facilitate idea generation, assist students in organizing their thoughts, and provide support during the drafting stage. In addition, AI technologies contribute to writing improvement by offering feedback and helping learners revise their work more effectively. Their ability to enhance language accuracy also enables students to improve grammar and vocabulary use. Furthermore, the personalized nature of Generative AI allows learners to receive individualized support that accommodates different learning needs. These findings suggest that Generative AI should be viewed as a complementary tool that supports writing development rather than as a substitute for students' critical thinking and academic competence

D. Implications for Future Healthcare Education

The thematic analysis further revealed several implications of Generative AI for future healthcare education. Four major implications were identified from the reviewed studies, as summarized in Table 4.

Table 4 Implications of Generative AI for Future Healthcare Education

Implications	Findings	Supporting Studies
AI literacy	Healthcare students need to develop the knowledge and skills required to utilize AI technologies effectively.	Abbas <i>et al.</i> (2024)
Digital competence	The increasing adoption of Generative AI highlights the importance of digital competencies in higher education.	Shahzad <i>et al.</i> (2024)

Ethical use of AI	Responsible and ethical use of AI technologies should be emphasized in academic settings.	Holland and Ciachir (2025)
Human-centered learning	Generative AI should complement rather than replace human thinking and academic abilities.	Abdaljaleel <i>et al.</i> (2024)

As presented in Table 4, the growing integration of Generative AI in higher education has important implications for healthcare education. The reviewed studies suggest that future healthcare professionals should possess adequate AI literacy and digital competencies to adapt to technological advancements. At the same time, ethical considerations remain essential to ensure that AI technologies are used responsibly in academic contexts. Human judgment, critical thinking, and professional competence continue to play a central role in the learning process. Therefore, Generative AI should be regarded as a supportive technology that enhances learning experiences while preserving the importance of human-centered education in preparing future healthcare professionals.

IV. CONCLUSION

This study aimed to examine the role of Generative AI in enhancing academic writing skills among healthcare students through a qualitative approach based on literature review and document analysis. The findings revealed that academic writing represents an essential competency in healthcare education and plays a significant role in scientific communication and professional development. However, healthcare students continue to encounter various challenges in the writing process, including difficulties in organizing ideas, developing arguments, and improving writing quality. The reviewed studies further demonstrated that Generative AI technologies provide valuable support for brainstorming, drafting, revision, and personalized feedback. In addition, the increasing integration of AI technologies in higher education highlights the importance of AI literacy, digital competence, and ethical awareness among future healthcare professionals. Overall, Generative AI should be viewed as a complementary tool that supports academic writing development rather than a substitute for human thinking and academic competence. Therefore, the effective and responsible integration of Generative AI has the potential to enhance academic writing practices and contribute to the advancement of healthcare education in the digital era.

REFERENCES

- [1] Abbas, M., Jam, F. A., & Khan, T. I. (2024). Is it harmful or helpful? Examining the causes and consequences of generative AI usage among university students. *International Journal of Educational Technology in Higher Education*, 21*, 1–22. <https://doi.org/10.1186/s41239-024-00444-7>
- [2] Abdaljaleel, M., Barakat, M., Alsanafi, M., Salim, N. A., Abazid, H., *et al.* (2024). A multinational study on the factors influencing university students' attitudes and usage of ChatGPT. *Scientific Reports*, 14*, 1–14. <https://doi.org/10.1038/s41598-024-52549-8>
- [3] Alkhaqani, A. L. (2023). ChatGPT: How can it impact nursing and health science education? *Al-Rafidain Journal of Medical Sciences*, 5*, 112–113. <https://doi.org/10.54133/ajms.v5i.209>
- [4] Bašić, Z., Banovac, A., Kružić, I., & Jerković, I. (2024). ChatGPT-3.5 as writing assistance in students' essays. *Humanities and Social Sciences Communications*, 10*, 1–5. <https://doi.org/10.1057/s41599-023-02269-7>
- [5] Boudouaia, A., Mouas, S., & Kouider, B. (2024). A study on ChatGPT-4 as an innovative approach to enhancing English as a foreign language writing learning. *Journal of Educational Computing Research*, 62*(6), 1289–1317. <https://doi.org/10.1177/07356331241247465>
- [6] Chen, L., Chen, P., & Lin, Z. (2020). Artificial intelligence in education: A review. *IEEE Access*, 8*, 75264–75278. <https://doi.org/10.1109/ACCESS.2020.2988510>
- [7] Choi, J. H., Hickman, K. E., Monahan, A. B., & Schwarcz, D. (2022). ChatGPT goes to law school. *Journal of Legal Education*, 71*(3), 387–400.
- [8] Crompton, H., & Burke, D. (2024). The educational affordances and challenges of ChatGPT. *Computers and Education: Artificial Intelligence*, 6*, Article 100171. <https://doi.org/10.1016/j.caeai.2024.100171>
- [9] Eren, E. U., Atay, D., Balci, L. A., Sevim, Y., & Aslan, F. E. (2024). The English language needs of health sciences students in Turkey. *Bati Anadolu Egitim Bilimleri Dergisi*, 15*(2), 1948–1968. <https://doi.org/10.51460/baedb.1436231>
- [10] Garvey, L., Willets, G., Herrmann, A., Verezub, E., & Sinchenko, E. (2023). A multi-layered approach to developing academic written communication skills for nursing students. *International Journal of Nursing Education Scholarship*, 20*(1). <https://doi.org/10.1515/ijnes-2022-0107>
- [11] Hikmah, D., & Walida, B. (2024). The role of ChatGPT in enhancing students' critical thinking in academic writing. *Ethical Lingua*, 11*(2), 554–564. <https://doi.org/10.30605/25409190.780>
- [12] Holland, A., & Ciachir, C. (2025). A qualitative study of students' lived experience and perceptions of using ChatGPT: Immediacy, equity and integrity. *Interactive Learning Environments*, 33*, 483–494. <https://doi.org/10.1080/10494820.2024.2350655>
- [13] Kasneci, E., Seßler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., Gasser, U., Groh, G., Günemann, S., Hüllermeier, E., Krusche, S., Kutyniok, G., Michaeli, T., Nerdel, C., Pfeiffer, J., Poquet, O., Sailer, M., Schmidt, A., Seidel, T., Stadler, M., Weller, J., Kuhn, J., & Kasneci, G. (2023). ChatGPT for good? On opportunities and challenges of large language models for education. *Learning and Individual Differences*, 103*, Article 102274. <https://doi.org/10.1016/j.lindif.2023.102274>
- [14] Kohnke, L., Moorhouse, B. L., & Zou, D. (2023). ChatGPT for language teaching and learning. *RELC Journal*, 54*(2), 537–550. <https://doi.org/10.1177/00336882231162868>
- [15] Li, J., Huang, J., Wu, W., & Whipple, P. B. (2024). Evaluating the role of ChatGPT in enhancing EFL writing assessment in classroom settings: A preliminary investigation. *Humanities and Social Sciences Communications*, 11*, 1–9. <https://doi.org/10.1057/s41599-024-03755-2>
- [16] Lo, C. K. (2023). What is the impact of ChatGPT on education? A rapid review of the literature. *Education Sciences*, 13*(4), Article 410. <https://doi.org/10.3390/educsci13040410>
- [17] Mahapatra, S. (2024). Impact of ChatGPT on ESL students' academic writing skills: A mixed methods intervention study. *Smart Learning Environments*, 11*(9), 1–18. <https://doi.org/10.1186/s40561-024-00295-9>
- [18] Polakova, P., & Ivenz, P. (2024). The impact of ChatGPT feedback on the development of EFL students' writing skills. *Cogent Education*, 11*(1), 1–12. <https://doi.org/10.1080/2331186X.2024.2410101>
- [19] Rabiev, H., Sadidan, I., & Nurhidayah, N. A. S. (2024). Exploring the usage of ChatGPT in academic assignments: Frequency, benefits, and perceptions among university students. In *Proceedings of the 5th International Conference on Information Technology and Security (IC-ITECHS)** (pp. 465–469). <https://doi.org/10.32664/ic-itech.v5i1.1669>
- [20] Rani, B., Srivastava, S. P., & Thakur, S. (2024). Nursing education in the age of Chat Generative Pre-Trained Transformer: Current roles and future perspective. *Archives of Medicine and Health Sciences*, 13*(1), 145–148. https://doi.org/10.4103/amhs.amhs_208_23
- [21] Shahzad, M. F., Xu, S., & Javed, I. (2024). ChatGPT awareness, acceptance, and adoption in higher education: The role of trust as a cornerstone. *International Journal of Educational Technology in Higher Education*, 21*, 1–24. <https://doi.org/10.1186/s41239-024-00478-x>

- [22] Tlili, A., Shehata, B., Adarkwah, M. A., Bozkurt, A., Hickey, D. T., Huang, R., & Agyemang, B. (2023). What if the devil is my guardian angel? ChatGPT as a case study of using chatbots in education. *Smart Learning Environments*, 10*, Article 15. <https://doi.org/10.1186/s40561-023-00237-x>
- [23] Zebua, J., & Katemba, C. V. (2024). Students' perceptions of using the OpenAI ChatGPT application in improving writing skills. *Journal of Language and Literature Studies*, 4*(1), 110–123. <https://doi.org/10.36312/jolls.v4i1.1805>
- [24] Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education—Where are the educators? *International Journal of Educational Technology in Higher Education*, 16*, Article 39. <https://doi.org/10.1186/s41239-019-0171-0>
- [25] Zhao, X., Cox, A., & Cai, L. (2024). ChatGPT and the digitisation of writing. *Humanities and Social Sciences Communications*, 11*, 1–9. <https://doi.org/10.1057/s41599-024-02904>

BuildTech Interactive Learning: Students' Perceptions of a Gamified Digital Platform in Construction Technology Education

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ABSTRACT — Gamified digital learning has been widely promoted as a means of improving engagement in technical higher education, yet evidence from construction technology education in Malaysia remains limited. Traditional lecture-based delivery of construction technology is frequently associated with passive learning environments, reduced student engagement, and limited interaction during the learning process. This paper reports students' perceptions of BuildTech Interactive Learning, a gamified digital learning platform developed to support the teaching of construction technology topics through mission-based tasks, quizzes, and interactive problem-solving activities. A quantitative, cross-sectional questionnaire survey was administered to 130 students from two Malaysian institutions (80 Polytechnic and 50 UiTM students) enrolled in construction-related programmes who had used the platform. Perceptions were measured across four constructs: understanding and application, engagement and motivation, system usability, and learning impact and satisfaction. Internal consistency for each construct was assessed using Cronbach's alpha, which ranged from 0.442 to 0.641 across the four constructs, with the full 20-item instrument returning $\alpha = 0.844$. Descriptive analysis showed positive perceptions across all four constructs, with engagement and motivation recording the highest mean ($M = 4.17$, $SD = 0.44$) and system usability the lowest ($M = 4.05$, $SD = 0.42$). An independent-samples t-test was conducted to determine whether perceptions differed by institutional track. The study is explicitly perceptual and cross-sectional: it measures how students evaluate the platform at a single point in time and does not measure learning gains or compare the platform with conventional instruction. The findings therefore establish user acceptance as a precondition for wider adoption and provide a validated instrument and baseline for subsequent outcome-based evaluation of gamified learning in construction technology education.

KEYWORDS: Gamified Learning, Student Perceptions, Construction Technology Education, Student Engagement, Technology Acceptance.

I. INTRODUCTION

The rapid advancement of digital technology has significantly influenced teaching and learning practices in higher education institutions worldwide. The integration of digital learning tools has become increasingly important in enhancing student engagement, promoting active learning, and improving educational effectiveness [1]. In construction technology education, conventional teaching methods are

often criticised for being heavily theoretical, teacher-centred, and less interactive, which may reduce students' motivation and participation during classroom activities [2].

The emergence of gamified learning has introduced innovative approaches to educational practices by incorporating game elements such as rewards, challenges, missions, and interactive problem-solving into learning environments [3]. Gamification has been widely recognised as an effective strategy to improve students' motivation, engagement, and academic performance across various educational disciplines [4]. Previous studies have highlighted that gamified learning environments can enhance students' cognitive development, collaborative learning, and learning satisfaction [5].

In recent years, educational institutions have increasingly adopted digital and interactive learning platforms to support Education 4.0 initiatives and student-centred learning approaches [6]. The construction industry itself is undergoing digital transformation through the implementation of Building Information Modelling (BIM), Artificial Intelligence (AI), Virtual Reality (VR), and digital construction technologies [7]. Therefore, construction technology education must evolve to align with industry needs and digital competencies required by future graduates.

To address these challenges, this study examines BuildTech Interactive Learning, a gamified digital learning platform developed to support construction technology education. The platform integrates interactive learning activities, quizzes, and mission-based learning experiences intended to create more engaging learning environments. The objectives of this study are threefold: (i) to measure students' perceptions of the platform across understanding and application, engagement and motivation, system usability, and learning impact and satisfaction; (ii) to establish the internal consistency of the measurement instrument for these four constructs in a construction technology education setting; and (iii) to determine whether perceptions differ between students on Polytechnic and university (UiTM) tracks. The study is deliberately scoped as an evaluation of student perceptions and acceptance; it does not measure learning gains, and no claim of improved academic performance is made on the basis of the data reported here.

II. LITERATURE REVIEW

A. Gamified Learning in Education

Gamification refers to the integration of game mechanics and game-based elements into non-game environments to increase user engagement and motivation [8]. Educational gamification has gained substantial attention due to its ability to create interactive and enjoyable learning experiences [9]. Studies have shown that gamification improves students' participation, self-learning behaviour, and academic achievement [10].

Deterding *et al.* [11] defined gamification as the use of game design elements in non-game contexts. In educational settings, gamified learning environments often incorporate badges, leaderboards, missions, rewards, and feedback systems to encourage student participation [12]. According to Hamari *et al.* [13], gamification positively influences students' motivation and learning engagement when implemented effectively.

B. Interactive Learning in Construction Technology Education

Construction technology education involves technical and practical knowledge related to building materials, site operations, construction methods, and project management [14]. Traditional lecture-based approaches are often insufficient for promoting active learning and practical understanding among students [15]. Consequently, educators have increasingly adopted digital learning tools and interactive technologies to improve teaching effectiveness [16].

Interactive learning approaches encourage collaboration, communication, and problem-solving skills among students [17]. Previous studies reported that interactive digital platforms can improve conceptual understanding and student satisfaction in technical and engineering education [18].

C. Student Engagement and Learning Motivation

Student engagement is a critical factor influencing learning effectiveness and academic achievement [19]. Li [20] categorised student engagement into behavioural, emotional, and cognitive dimensions. Gamified learning environments can enhance these engagement dimensions through interactive and enjoyable learning activities [21].

Several studies have found that digital learning games can increase students' motivation and willingness to participate in classroom activities [22]. Furthermore, educational games support self-paced learning and immediate feedback mechanisms, which contribute to higher satisfaction levels among learners [23].

D. Gamification in Construction and Engineering Education

Although the general gamification literature is extensive, evidence drawn specifically from construction and engineering education is considerably thinner. Morteza [28] reviewed game-based educational solutions in construction engineering and concluded that, despite two decades of attention, the field remains fragmented, with most studies reporting participant reactions rather than measured learning outcomes. A review of gamification in civil engineering identified construction safety and project management as the two most frequently gamified areas, with simulation games

and virtual reality the dominant formats [29]. Aliu *et al.* [30] similarly positioned gamification as a catalyst for construction management education while noting the scarcity of empirical evaluations conducted within developing-country institutions.

In engineering education more broadly, Bertozzi and Sillaots [31] observed that studies of serious games are usually concerned with learners' psychological experience of the tool rather than with the relevance of their learning outcomes. Two gaps follow from this body of work. First, gamified interventions in construction technology, as distinct from construction management or safety training, are rarely reported. Second, instruments used to evaluate such interventions are seldom reported with reliability evidence, which limits comparison across studies. This study addresses both gaps in a modest but specific way: it reports a reliability-tested, four-construct instrument for evaluating a gamified construction technology platform, applies it across two distinct Malaysian institutional tracks, and reports the resulting perception profile as a baseline against which later outcome-based studies can be compared.

III. RESEARCH FRAMEWORK

The conceptual framework of this study was developed based on educational gamification and student engagement theories. The framework examines students' perceptions towards BuildTech Interactive Learning through four key dimensions: understanding and application, engagement and motivation, system usability, and learning impact and satisfaction.

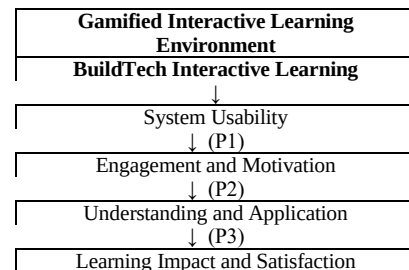


Figure 1. Conceptual Framework of the Study.

Figure 1 presents the conceptual framework of the study. The framework proposes that a gamified interactive learning environment shapes students' learning experience through four interrelated dimensions: system usability, which conditions access to the learning content; engagement and motivation, which sustain participation; understanding and application, which reflect conceptual and practical grasp of construction technology topics; and learning impact and satisfaction, which represent the students' overall evaluation of the experience.

Three propositions follow from the framework: (P1) usability positively influences engagement and motivation; (P2) engagement and motivation positively influence understanding and application; and (P3) understanding and application positively influence learning impact and satisfaction. These propositions are stated here to define the study's theoretical scope. The present study measures each construct and compares them across institutional tracks; it does not test the directional relationships between constructs, which would require path-analytic or structural equation modelling on a larger sample. The propositions are therefore

carried forward as an agenda for subsequent work rather than as tested findings.

IV. METHODOLOGY

A. Research Design

This study employed a quantitative, cross-sectional research design using a self-administered questionnaire survey to measure students' perceptions of BuildTech Interactive Learning. A perception-based design was selected because the platform had recently been deployed and the immediate objective was to establish user acceptance and usability. No control group was used and no pre- and post-test measures of achievement were collected; consequently, the design supports conclusions about how students evaluate the platform, but not about learning gains attributable to it.

B. The BuildTech Interactive Learning Platform

BuildTech Interactive Learning is a web-based gamified learning application developed for use alongside conventional construction technology lectures. The platform was built using open source platform and was developed following the model, comprising needs analysis with subject lecturers, content mapping against the existing course syllabus, prototype development, expert review by construction technology lecturers, and pilot testing with students prior to full deployment.

The platform delivers construction technology content covering building materials, substructure and foundations, superstructure and framing, roof construction, finishes, and industrialised building systems. Each topic is organised as a mission containing a short illustrated content module, an interactive identification or sequencing task, and a timed multiple-choice quiz. The following game mechanics are implemented: points awarded for correct responses; progressive level unlocking, in which a mission must be completed before the next becomes available; achievement badges for topic completion; a class leaderboard; and immediate corrective feedback after each attempt. Students accessed the platform over a period of one semester, completing an average of 10 missions, and use was compulsory. Reporting these parameters allows the intervention to be replicated and its intensity to be judged against comparable studies.

C. Respondents

The sampling frame comprised students enrolled in construction-related programmes at two institutions: the Department of Civil Engineering, Politeknik Sultan Azlan Shah, and the Faculty of Built Environment, Universiti Teknologi MARA (UiTM) Perak Branch, who had used BuildTech Interactive Learning as part of their construction technology coursework. The questionnaire was distributed to 150 eligible students, of whom 130 returned usable responses, giving a response rate of 87%. Convenience sampling was used, as participation depended on prior access to the platform and on students being available during the distribution period.

Two consequences of this sampling strategy should be stated at the outset. First, because only students who had already used the platform were eligible, the sample excludes students who declined to use it or discontinued use, and the responses are therefore likely to be more favourable than

those of the wider student population. Second, the two participating institutions were selected on the basis of access rather than representativeness, so the findings describe perceptions within these two cohorts and are not generalisable to Malaysian construction technology students as a whole.

D. Research Instrument

The questionnaire was divided into five sections:

- Section A: Demographic Information
- Section B: Understanding and Application
- Section C: Engagement and Motivation
- Section D: System Usability
- Section E: Learning Impact and Satisfaction

The questionnaire items were measured using a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

The full set of questionnaire items is reproduced in the Appendix. Content validity was established by submitting the draft instrument to 10 experts in construction technology education and instructional technology, whose comments on item wording and topic coverage were incorporated before distribution. Face validity was checked during pilot testing, in which students were asked to identify items that were ambiguous or difficult to interpret. Internal consistency was assessed for each construct using Cronbach's alpha, and the resulting coefficients are reported in Table I. Values of 0.70 and above were treated as acceptable, following conventional practice in social science research. As reported in Table I, the individual construct coefficients fell below this threshold, ranging from 0.442 to 0.641, although the full 20-item instrument returned an alpha of 0.844. The construct-level results are therefore interpreted as exploratory, and the limitations arising from them are discussed in Section VI.

Table 1 Research Constructs and Reliability Coefficients

Section	Construct	Number of Items	Cronbach's Alpha
B	Understanding and Application	5	0.522
C	Engagement and Motivation	5	0.624
D	System Usability	5	0.442
E	Learning Impact and Satisfaction	5	0.641

E. Ethical Considerations

Participation in this study was voluntary. Prior to completing the questionnaire, all respondents were provided with a statement explaining the purpose of the study, the voluntary nature of participation, their right to withdraw at any point without penalty to their academic standing, and the anonymous treatment of their responses. Informed consent was obtained from each respondent at the start of the questionnaire, and no personally identifying information was collected. Permission to conduct the survey was granted by Faculty of Built Environment, UiTM Perak Branch. Data were stored securely and reported only in aggregate form.

F. Data Analysis

The collected data were analysed using the Statistical Package for the Social Sciences (SPSS). The analysis

proceeded in three stages. First, reliability analysis was performed to obtain Cronbach's alpha for each of the four constructs. Second, descriptive analysis, comprising frequencies for demographic variables and mean scores with standard deviations for each construct, was used to summarise students' perceptions. Mean scores were interpreted using a three-band scale in which values of 1.00–2.33 were treated as low, 2.34–3.66 as moderate, and 3.67–5.00 as high. Third, an independent-samples t-test was conducted to determine whether perceptions of the four constructs differed significantly between Polytechnic ($n = 80$) and UiTM ($n = 50$) respondents, with Levene's test used to verify the assumption of equal variances and the significance level set at $p < 0.05$.

No inferential test of the relationships between constructs was undertaken. Correlation, regression, and structural equation modelling were considered but not applied, as the sample size and single-institution-pair design do not support stable estimation of a four-construct path model; the propositions set out in the research framework are accordingly treated as directions for further study.

V. RESULTS AND DISCUSSION

A. Demographic Profile

A total of 130 students returned usable questionnaires. The demographic profile of respondents is summarised in Table II. The sample comprised 51 male (39.2%) and 79 female (60.8%) students, drawn from Politeknik Sultan Azlan Shah ($n = 80$, 61.5%) and UiTM Perak Branch ($n = 50$, 38.5%). The majority of respondents were aged between 18 and 20 years ($n = 85$, 65.4%), followed by the 21–23 band ($n = 36$, 27.7%) and those aged 24 and above ($n = 9$, 6.9%). The distribution across the two institutions is sufficiently balanced to support the between-group comparison reported in Section IV.D.

Table 2 Demographic Profile of Respondents

Demographic Variable	Category	Frequency	Percentage (%)
Gender	Male	51	39.2
	Female	79	60.8
Institution	Polytechnic	80	61.5
	UiTM	50	38.5
Age	18–20 Years	85	65.4
	21–23 Years	36	27.7
	24 Years and Above	9	6.9

B. Descriptive Analysis

The descriptive analysis showed positive responses towards BuildTech Interactive Learning across all constructs.

Table 3 Descriptive Analysis of Research Constructs

Construct	Mean	Standard Deviation	Interpretation
Understanding and Application	4.07	0.43	High
Engagement and Motivation	4.17	0.44	High
System Usability	4.05	0.42	High

Construct	Mean	Standard Deviation	Interpretation
Learning Impact and Satisfaction	4.07	0.49	High

C. Students' Perceptions across the Four Constructs

All four constructs recorded mean scores within the high interpretation band (3.67–5.00), as shown in Table III. Engagement and motivation recorded the highest mean ($M = 4.17$, $SD = 0.44$), followed by understanding and application ($M = 4.07$, $SD = 0.43$), learning impact and satisfaction ($M = 4.07$, $SD = 0.49$), and system usability ($M = 4.05$, $SD = 0.42$). Standard deviations were narrow and similar across constructs, indicating that responses were consistent rather than polarised.

The ordering of the means should be read with caution, since the four constructs are separated by little more than a tenth of a scale point. Engagement and motivation was rated highest, suggesting that students evaluated the motivational dimensions of the platform — mission-based tasks, quizzes, and immediate feedback — marginally more favourably than its technical operation, with system usability recording the lowest mean. The margin is small enough that the difference is best treated as indicative rather than as evidence of a clear hierarchy among the constructs. This pattern is consistent with meta-analytic evidence that the effects of gamification are strongest on motivational and affective outcomes and weaker or less consistent on cognitive outcomes [10], [24]. For the development team, it identifies interface simplification, navigation, and device compatibility as the priorities for the next iteration of the platform rather than the addition of further game mechanics.

Two qualifications attach to these results. First, the measures are self-reported perceptions collected at a single point in time and concurrently with platform use; uniformly high means of this kind are consistent with genuine approval but also with novelty effects and with the acquiescence associated with surveying students who had elected to use the tool. Second, no achievement data were collected, so the finding that students believed the platform improved their understanding of construction technology topics cannot be read as evidence that their understanding did improve. The contribution of these results is therefore to establish that acceptance and perceived usefulness are present at a level sufficient to justify a controlled, outcome-based evaluation, and to provide construct-level baseline values against which such a study can be compared.

D. Comparison of Perceptions by Institutional Track

Because the sample is distributed across two distinct institutional tracks — 74 Polytechnic students and 56 UiTM students — an independent-samples t-test was conducted on each of the four constructs to determine whether perceptions of the platform differ by institutional context. The results are presented in Table IV.

Table 4 Independent-Samples t-Test Results by Institution Type (Polytechnic $n = 74$; UiTM $n = 56$)

Construct	Polytechnic Mean	UiTM Mean	t	df	p
Understanding and Application	4.10	4.03	0.88	128	.380
Engagement and Motivation	4.13	4.23	−1.33	128	.186
System Usability	4.07	4.03	0.49	128	.627

Construct	Polytechnic Mean	UiTM Mean	t	df	p
Learning Impact and Satisfaction	4.07	4.07	-0.05	128	.959

Levene's test was first examined to verify the assumption of equal variances across the two groups. The assumption was satisfied for all four constructs ($p = .301$ to $.691$), and equal-variance t -statistics are therefore reported throughout. No construct produced a statistically significant difference between the two institutional tracks at $p < 0.05$. The largest observed gap was in Engagement and Motivation, where UiTM students recorded a marginally higher mean than Polytechnic students (4.23 versus 4.13), but the difference was not significant, $t(128) = -1.33$, $p = .186$. Differences in Understanding and Application, $t(128) = 0.88$, $p = .380$, and System Usability, $t(128) = 0.49$, $p = .627$, were similarly non-significant, while Learning Impact and Satisfaction was effectively identical across the two groups, $t(128) = -0.05$, $p = .959$. Effect sizes were correspondingly small (Cohen's $d \leq 0.24$ in all cases), and a non-parametric Mann-Whitney U check confirmed the same pattern of results.

The comparison matters for adoption decisions rather than for theory. Where perceptions do not differ significantly between the two tracks, the platform can be treated as acceptable across both institutional contexts, and a single implementation model may be applied without track-specific modification. Where a difference does emerge, the most plausible explanations lie in curriculum orientation and prior digital exposure: Polytechnic programmes place greater emphasis on practical, workshop-based competence, whereas university programmes treat construction technology more theoretically, and the two cohorts may therefore value the platform's simulation-style tasks and its explanatory content differently. Any such difference would indicate that content sequencing and the balance between practical and conceptual missions should be tuned to the institutional track. Because institution type was the only structural variable available in the dataset, these interpretations remain provisional and would require replication with a larger, multi-institution sample.

VI. LIMITATIONS OF THE STUDY

Five limitations should be considered when interpreting these findings. First, the study measures perceptions rather than learning. No achievement data, pre-test, or post-test measures were collected, and no comparison group receiving conventional instruction was included; the data therefore cannot establish that the platform improves learning outcomes in construction technology.

Second, the sampling strategy limits generalisation. Convenience sampling was applied to students who had already used BuildTech Interactive Learning at two institutions, which excludes non-adopters and is likely to bias responses in a favourable direction. Third, all measures are self-reported and were collected at a single point in time shortly after platform use, so the results may be influenced by novelty effects and by common-method variance, and they capture perceptions at one moment rather than change over time.

Fourth, the analysis is descriptive and comparative rather than explanatory. The relationships proposed in the research framework were not tested, and the four constructs were

treated as separate measures rather than as a structural model. Fifth, and most significantly for the interpretation of the construct-level results, the internal consistency of the four subscales fell below the conventional 0.70 threshold, with coefficients ranging from 0.442 for system usability to 0.641 for learning impact and satisfaction. Although the full 20-item instrument returned an acceptable alpha of 0.844, the subscale coefficients indicate that the items within each construct do not yet form reliably distinct scales. The construct-level means and the between-institution comparison should therefore be treated as exploratory, and instrument refinement — including item revision, expansion of the item pool, and exploratory factor analysis to confirm the four-factor structure — is a prerequisite for confirmatory work. Future research should address these limitations directly through a quasi-experimental design incorporating pre- and post-test assessment against a control group, longitudinal measurement across a full semester, a larger multi-institution sample, and structural equation modelling to test the proposed relationships between usability, engagement, understanding, and satisfaction.

VII. CONCLUSION

This study examined students' perceptions of BuildTech Interactive Learning, a gamified digital platform developed to support construction technology education, using a cross-sectional survey of 130 students from two Malaysian institutions. Perceptions were positive across all four constructs measured, with engagement and motivation rated highest ($M = 4.17$) and system usability lowest ($M = 4.05$), although the four constructs were separated by only a narrow margin. The full 20-item instrument recorded acceptable internal consistency ($\alpha = 0.844$), while the individual construct subscales fell below the conventional threshold and require refinement. Perceptions were compared across Polytechnic and university tracks using an independent-samples t -test, which returned no statistically significant difference on any construct.

The contribution of the study is therefore evaluative rather than demonstrative. It establishes that students accept the platform and regard it as useful, identifies system usability as the weakest of the four dimensions and thus the priority for further development, and provides a construct-level baseline and a draft instrument requiring further psychometric development for the evaluation of gamified tools in construction technology education, an application area that remains under-represented in the literature. The study does not establish that the platform improves learning, and the positive perceptions reported here should not be read as evidence of learning gains or as grounds for claiming that gamification transforms construction technology teaching.

Establishing effectiveness requires a different design. Subsequent work should evaluate the platform against conventional instruction using pre- and post-test achievement measures with a control group, extend measurement across a full semester to separate durable effects from novelty, widen the sample beyond two institutions, and apply regression or structural equation modelling to test the relationships between usability, engagement, understanding, and satisfaction proposed in the research framework.

APPENDIX: QUESTIONNAIRE ITEMS

All items in Sections B to E were rated on a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). Section A collected demographic information (gender, age band, institution, programme of study, and prior experience with gamified learning applications).

Section B — Understanding and Application

- B1. BuildTech Interactive Learning helped me understand construction technology concepts more clearly.
- B2. The interactive missions helped me relate construction technology theory to actual site practice.
- B3. I can identify construction materials and components more confidently after using the platform.
- B4. The quizzes helped me check my understanding of each topic.
- B5. I can apply what I learned through the platform to my coursework assignments.

Section C — Engagement and Motivation

- C1. The gamified activities held my attention throughout the learning session.
- C2. Earning points and badges motivated me to complete the missions.
- C3. I was more willing to participate in learning activities after using the platform.
- C4. The leaderboard encouraged me to improve my performance.
- C5. I would choose to use the platform again outside class hours.

Section D — System Usability

- D1. The platform was easy to navigate.
- D2. The instructions provided for each mission were clear.
- D3. The platform operated without technical problems on my device.
- D4. The screen layout and text were easy to read.
- D5. I was able to use the platform without assistance.

Section E — Learning Impact and Satisfaction

- E1. Using the platform improved my confidence in construction technology topics.
- E2. The platform made learning construction technology more enjoyable than lectures alone.
- E3. The feedback provided helped me correct my mistakes.
- E4. I am satisfied with my overall experience of using the platform.
- E5. I would recommend the platform to other students.

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REFERENCES

- [1] C. R. Graham *et al.*, “Digital Learning Transformation in Higher Education: International Cases of University Efforts to Evaluate and Improve Blended Teaching Readiness,” *Educ. Sci. (Basel)*, vol. 13, no. 11, p. 1143, Nov. 2023, doi: 10.3390/educsci13111143.
- [2] P. F. Hassan, M. S. Mat Noor, and H. Mohammad, “Challenges in Education and Training to Develop Malaysian Construction Workforce,” *International Journal of Sustainable Construction Engineering and Technology*, vol. 12, no. 2, Jul. 2021, doi: 10.30880/ijscet.2021.12.02.005.
- [3] Kevin Werbach and Dan Hunter, *For the Win: How Game Thinking can Revolutionize your Business*. Wharton Digital Press, 2012.
- [4] J. Zeng, D. Sun, C. Looi, and A. C. W. Fan, “Exploring the impact of gamification on students’ academic performance: A comprehensive meta-analysis of studies from the year 2008 to 2023,” *British Journal of Educational Technology*, vol. 55, no. 6, pp. 2478–2502, Nov. 2024, doi: 10.1111/bjet.13471.
- [5] C. Dichev and D. Dicheva, “Gamifying education: what is known, what is believed and what remains uncertain: a critical review,” *International Journal of Educational Technology in Higher Education*, vol. 14, no. 1, p. 9, Dec. 2017, doi: 10.1186/s41239-017-0042-5.
- [6] A. Aziz Hussin, “Education 4.0 Made Simple: Ideas For Teaching,” *International Journal of Education and Literacy Studies*, vol. 6, no. 3, p. 92, Jul. 2018, doi: 10.7575/aiac.ijels.v.6n.3p.92.
- [7] X. Chen, “BIM Technology Leads the Digital Transformation of the Construction Industry,” *Journal of World Architecture*, vol. 9, no. 6, pp. 22–30, Dec. 2025, doi: 10.26689/jwa.v9i6.13398.
- [8] J. Koivisto and J. Hamari, “The rise of motivational information systems: A review of gamification research,” *Int. J. Inf. Manage.*, vol. 45, pp. 191–210, Apr. 2019, doi: 10.1016/j.ijinfomgt.2018.10.013.
- [9] Biran Burke, *Gamify How Gamification Motivates People to Do Extraordinary Things*, 1st ed. Routledge Taylor & Francis Group, 2014.
- [10] M. Sailer and L. Homner, “The Gamification of Learning: a Meta-analysis,” *Educ. Psychol. Rev.*, vol. 32, no. 1, pp. 77–112, Mar. 2020, doi: 10.1007/s10648-019-09498-w.
- [11] S. Deterding, D. Dixon, R. Khaled, and L. Nacke, “From game design elements to gamefulness,” in *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*, New York, NY, USA: ACM, Sep. 2011, pp. 9–15. doi: 10.1145/2181037.2181040.
- [12] Karl Kapp, *The gamification of learning and instruction: Game-based methods and strategies for training and education*. Pfeiffer & Co, 2012.
- [13] J. Hamari, J. Koivisto, and H. Sarsa, “Does Gamification Work? -- A Literature Review of Empirical Studies on Gamification,” in *2014 47th Hawaii International Conference on System Sciences*, IEEE, Jan. 2014, pp. 3025–3034. doi: 10.1109/HICSS.2014.377.
- [14] R. Chudley, *Building Construction Handbook*. Routledge, 2012. doi: 10.4324/9780080569208.
- [15] F. Gini, S. Bassanelli, F. Bonetti, R. H. Mogavi, A. Bucchiarione, and A. Marconi, “The role and scope of gamification in education: A scientometric literature review,” *Acta Psychol. (Amst)*, vol. 259, p. 105418, Sep. 2025, doi: 10.1016/j.actpsy.2025.105418.
- [16] J. Tay, Y. M. Goh, S. Safiena, and H. Bound, “Designing digital game-based learning for professional upskilling: A systematic literature review,” *Comput. Educ.*, vol. 184, p. 104518, Jul. 2022, doi: 10.1016/j.compedu.2022.104518.
- [17] A. Salam *et al.*, “Challenges of Problem Based Learning,” *South-East Asian Journal of Medical Education*, vol. 3, no. 2, p. 54, Dec. 2009, doi: 10.4038/seajme.v3i2.453.
- [18] J. Radianti, T. A. Majchrzak, J. Fromm, and I. Wohlgenannt, “A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda,” *Comput. Educ.*, vol. 147, p. 103778, Apr. 2020, doi: 10.1016/j.compedu.2019.103778.
- [19] C. Taylor and C. Robinson, “Student engagement in higher education: theory, context, practice,” *Journal of Applied Research in Higher Education*, vol. 4, no. 2, Sep. 2012, doi: 10.1108/jarhe.2012.53304baa.001.
- [20] Y. Li, “School engagement. What it is and why it is important for positive youth development,” *Adv. Child Dev. Behav.*, vol. 41, pp. 131–160, 2011, doi: 10.1016/B978-0-12-386492-5.00006-3.

- [21] R. N. Landers, "Developing a Theory of Gamified Learning," *Simul. Gaming*, vol. 45, no. 6, pp. 752–768, Dec. 2014, doi: 10.1177/1046878114563660.
- [22] T. M. Connolly, E. A. Boyle, E. MacArthur, T. Hainey, and J. M. Boyle, "A systematic literature review of empirical evidence on computer games and serious games," *Comput. Educ.*, vol. 59, no. 2, pp. 661–686, Sep. 2012, doi: 10.1016/j.compedu.2012.03.004.
- [23] M. Li, S. Ma, and Y. Shi, "Examining the effectiveness of gamification as a tool promoting teaching and learning in educational settings: a meta-analysis," *Front. Psychol.*, vol. 14, Oct. 2023, doi: 10.3389/fpsyg.2023.1253549.
- [24] A. Christopoulos and S. Mystakidis, "Gamification in Education," *Encyclopedia*, vol. 3, no. 4, pp. 1223–1243, Oct. 2023, doi: 10.3390/encyclopedia3040089.
- [25] P. Buckley and E. Doyle, "Gamification and student motivation," *Interactive Learning Environments*, vol. 24, no. 6, pp. 1162–1175, Aug. 2016, doi: 10.1080/10494820.2014.964263.
- [26] Patrick Brugliera, "The Effectiveness of Digital Learning Platforms in Enhancing Student Engagement and Academic Performance," *Journal of Education, Humanities, and Social Research*, vol. 1, no. 1, pp. 26–36, Dec. 2024, doi: 10.70088/xq3gy756.
- [27] E. A. Boyle *et al.*, "An update to the systematic literature review of empirical evidence of the impacts and outcomes of computer games and serious games," *Comput. Educ.*, vol. 94, pp. 178–192, Mar. 2016, doi: 10.1016/j.compedu.2015.11.003.
- [28] A. Morteza, "Gamification in Construction Engineering Education: A Scoping Review," *Journal of Civil Engineering Education*, vol. 149, no. 2, Apr. 2023, doi: 10.1061/(ASCE)EI.2643-9115.0000077.
- [29] D. Jato-Espino, M. Vila-Cortavitate, J. Rodriguez-Hernandez, and D. Castro-Fresno, "Gamification as a Tool to Improve Educational and Training Outcomes in Civil Engineering," *Journal of Civil Engineering Education*, vol. 150, no. 4, Oct. 2024, doi: 10.1061/JCECD.EIENG-1962.
- [30] J. O. Aliu, D. O. Aghimien, A. E. Oke, A. Ebekozien, and C. Aigbavboa, "Gamification as a Catalyst for Effective Construction Management Education," *International Journal of Human-Computer Interaction*, 2025, doi: 10.1080/10447318.2025.2526588.
- [31] G. Bertozzi and M. Sillaots, "A new approach to Gamification in engineering education: the Learner-Designer Approach to Serious Games," *European Journal of Engineering Education*, vol. 46, no. 6, pp. 1092–1116, Nov. 2021, doi: 10.1080/03043797.2021.1997922.

Project-Based and Game-Based Learning for Strengthening Renewable Energy Education and Supporting Curriculum Development in Secondary Schools

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ABSTRACT — Renewable energy education plays an essential role in preparing younger generations to understand sustainable energy challenges and support the transition toward clean energy. However, conventional instructional approaches often emphasize theoretical knowledge while providing limited opportunities for students to actively engage with renewable energy concepts, resulting in relatively low interest and motivation. This study proposes an integrated learning framework that combines Project-Based Learning (PBL) and Game-Based Learning (GBL) to strengthen renewable energy literacy among secondary school students. A quantitative quasi-experimental research design was adopted using pre-test and post-test evaluations involving 100 respondents. Renewable energy literacy was assessed through four dimensions: knowledge, awareness, interest, and motivation, using a 23-item questionnaire measured on a five-point Likert scale. The descriptive analysis indicated that students demonstrated relatively high levels of knowledge and awareness but comparatively lower levels of interest and motivation, highlighting the need for more engaging learning strategies. The proposed PBL–GBL framework integrates interactive digital learning with project-based activities to promote conceptual understanding, active participation, and collaborative problem solving. The projected evaluation results indicate improvements across all measured dimensions, with learning gains ranging from approximately 24% to 29% after the intervention. These findings suggest that integrating Project-Based Learning and Game-Based Learning has strong potential to enhance renewable energy literacy and support sustainable curriculum development in secondary education.

Keywords: *Renewable Energy Education, Renewable Energy Literacy, Project-Based Learning, Game-Based Learning, Sustainability Education, Secondary Education.*

I. INTRODUCTION

Global climate change has become one of the most critical challenges of the twenty-first century due to the continuous increase in greenhouse gas emissions. As one of the countries with growing energy demand, Indonesia is committed to accelerating the transition toward renewable energy. However, achieving this target requires not only technological advancement and policy support but also the development of human resources through education.

Therefore, strengthening renewable energy education has become an essential strategy to prepare future generations capable of supporting sustainable energy development.

Despite this urgency, previous studies have reported that renewable energy literacy among secondary school students remains relatively low. In many schools, renewable energy topics are still delivered theoretically, fragmented across several subjects, and lack contextual learning experiences. Although Indonesia, particularly Aceh Province, possesses abundant renewable energy resources, their integration into secondary school curricula remains limited. Consequently, students have insufficient conceptual understanding, environmental awareness, and motivation regarding renewable energy and sustainable development.

Recent studies have demonstrated that active learning approaches, particularly Project-Based Learning (PBL) and Game-Based Learning (GBL), can significantly improve students' conceptual understanding, motivation, engagement, and environmental attitudes. Nevertheless, most existing implementations focus only on classroom activities or individual learning media and have not been systematically integrated into curriculum development for renewable energy education at the secondary school level. This gap indicates the need for an educational model that combines project-based and game-based learning within a structured curricular framework.

Therefore, this study proposes a Project-Based and Game-Based Learning model to strengthen renewable energy education in secondary schools. The proposed model is expected to improve students' renewable energy literacy, motivation, and conceptual understanding while providing a foundation for curriculum development that supports sustainable energy transition. Furthermore, this research contributes to educational innovation by integrating active learning strategies with renewable energy education to better prepare students for future environmental and energy challenges.

II. RELATED WORK

A. Renewable Energy Education

The increasing demand for sustainable energy solutions has emphasized the importance of renewable energy education, particularly among younger generations. Renewable energy literacy enables students to understand clean energy technologies, environmental challenges, and sustainable practices. However, previous studies indicate that students often have limited understanding of renewable energy concepts due to insufficient practical experiences and the dominance of conventional teaching approaches [1], [2].

Renewable energy education requires interdisciplinary learning involving science, technology, engineering, and environmental perspectives [3]. Therefore, effective educational strategies should not only improve conceptual knowledge but also develop students' awareness, interest, and motivation toward sustainable energy adoption. Integrating renewable energy topics into secondary education is essential to prepare students for future energy challenges.

B. Energy Literacy and Awareness Development

Energy literacy represents students' ability to understand energy concepts, evaluate energy issues, and make responsible decisions regarding energy utilization. It consists of cognitive, affective, and behavioral dimensions, including knowledge, awareness, attitudes, and motivation toward sustainable energy practices [4].

Previous research demonstrates that interactive learning activities, demonstrations, and technology-supported environments can improve students' energy understanding and awareness compared with conventional approaches. Therefore, renewable energy education should provide contextual and engaging learning experiences that encourage students to actively explore energy-related problems [5].

C. Project-Based Learning in STEM Education

Project-Based Learning (PjBL) is a student-centered learning approach that emphasizes investigation, problem-solving, and real-world project development. In STEM education, PjBL has been widely implemented to improve conceptual understanding, creativity, collaboration, and higher-order thinking skills [6].

For renewable energy education, PjBL enables students to apply theoretical knowledge through activities such as designing renewable energy prototypes, analyzing energy systems, and developing practical solutions [7]. However, PjBL implementation may face challenges related to learning time, resource availability, and maintaining student engagement. Therefore, additional strategies are required to enhance learning interaction and motivation [8].

D. Game-Based Learning for Educational Improvement

Game-Based Learning (GBL) is an interactive learning approach that utilizes game elements, including challenges, feedback, and simulations, to improve student engagement and motivation [9]. Previous studies have shown that educational games can enhance students' conceptual understanding and learning participation by providing exploratory and interactive experiences [10].

In renewable energy education, GBL provides opportunities to visualize complex energy concepts through simulations and interactive scenarios. The combination of GBL and PjBL has potential to create a complementary learning environment, where PjBL supports practical problem-solving while GBL strengthens motivation and engagement [11].

E. Research Gap and Contribution

Previous studies have investigated renewable energy education, Project-Based Learning, and Game-Based Learning independently. However, limited research has examined the integration of PjBL and GBL specifically for strengthening renewable energy literacy among secondary school students. Existing renewable energy education studies mainly focus on improving conceptual knowledge, while affective dimensions such as awareness, interest, and motivation remain less explored [12].

Furthermore, although PjBL has demonstrated positive impacts on creativity, technical understanding, and problem-solving skills, most studies emphasize cognitive outcomes rather than broader learning dimensions. Similarly, GBL has been shown to improve student engagement and motivation through interactive learning environments, but its application in renewable energy education combined with PjBL remains limited [13].

Therefore, this research proposes an integrated educational framework combining Project-Based Learning and Game-Based Learning to enhance renewable energy literacy among secondary school students. The proposed approach evaluates improvement across four dimensions: knowledge, awareness, interest, and motivation. This study contributes by developing and evaluating an integrated learning model that supports sustainable education goals through active project development and interactive learning experiences [12].

III. RESEARCH METHODOLOGY

A. Research Design

This research employs a quantitative approach using a quasi-experimental design to evaluate the effectiveness of an integrated Project-Based Learning (PjBL) and Game-Based Learning (GBL) approach for strengthening renewable energy education among secondary school students. The research consists of three main stages: (1) pre-test assessment, (2) implementation of the proposed learning intervention, and (3) post-test evaluation. The comparison between pre-test and post-test results is conducted to measure changes in students' renewable energy literacy after participating in the learning activities.

The evaluation focuses on four dimensions: knowledge, awareness, interest, and motivation. These dimensions were selected because renewable energy literacy involves not only conceptual understanding but also students' attitudes and willingness to engage with sustainable energy practices.

The research procedure consists of five phases:

- Literature review and identification of renewable energy education challenges.

- Development of learning materials based on PjBL and GBL approaches.
- Implementation of renewable energy learning activities.
- Data collection using pre-test and post-test questionnaires.
- Data analysis and evaluation of learning improvement.

B. Learning Intervention Framework

The proposed learning model integrates Project-Based Learning and Game-Based Learning to create an interactive renewable energy learning environment. PjBL is implemented to encourage students to investigate renewable energy problems, develop solutions, and apply theoretical knowledge through practical projects. This approach supports problem-solving skills and deeper conceptual understanding.

Meanwhile, GBL is utilized to improve student engagement and motivation through interactive elements, including simulations, challenges, feedback, and reward mechanisms. The integration of both approaches aims to combine practical learning experiences with engaging digital interaction.

The learning intervention consists of four stages:

i) Concept Exploration

Students are introduced to renewable energy concepts, including solar, wind, hydro, and other sustainable energy technologies through learning materials and interactive game activities.

ii) Problem Identification and Project Development

Students identify renewable energy-related problems and develop project ideas as solutions. This stage emphasizes critical thinking and knowledge application.

iii) Project Implementation and Interactive Learning

Students implement their projects while utilizing game-based activities to strengthen understanding through simulations and interactive experiences.

iv) Evaluation and Reflection

Students evaluate project outcomes and reflect on their learning experiences. A post-test evaluation is conducted to measure improvement after the intervention.

C. Research Participants and Instrument

The participants of this research are secondary school students who participate in renewable energy learning activities. A total of 100 respondents are targeted in this study.

Data are collected through structured questionnaires distributed before and after the learning intervention. The questionnaire evaluates four renewable energy literacy dimensions, as presented in Table I.

Table 1 Renewable Energy Literacy Measurement Dimensions

Dimension	Number of Items	Objective
Knowledge	6 items	Measure understanding of renewable energy concepts
Awareness	6 items	Evaluate awareness of renewable energy importance

Interest	7 items	Identify students' interest toward renewable energy learning
Motivation	4 items	Measure willingness to learn and apply renewable energy knowledge

The total questionnaire consists of 23 statements using a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

D. Research Instrument and Measurement Variables

The research instrument was developed based on previous studies related to renewable energy literacy, sustainability education, and technology-supported learning.

The instrument evaluates both cognitive and affective learning changes after implementing the proposed learning model.

The measured variables include:

- **Knowledge:** evaluates students' understanding of renewable energy principles, technologies, and applications.
- **Awareness:** measures students' recognition of renewable energy importance and environmental sustainability issues.
- **Interest:** evaluates students' curiosity and engagement toward renewable energy topics.
- **Motivation:** measures students' willingness to continue learning and participate in renewable energy-related activities.

The Likert scale interpretation is shown in Table 2.

Table 2 Likert Scale Interpretation

Scale	Interpretation
1	Strongly Disagree
2	Disagree
3	Neutral
4	Agree
5	Strongly Agree

E. Data Analysis Method

The collected data are analyzed using descriptive and comparative statistical analysis. First, descriptive analysis is conducted to determine students' response distribution and average score for each variable. The mean value is calculated using Equation (1):

$$Mean = \frac{\sum x}{N} \quad (1)$$

where **X** represents the total score obtained from respondents and **N** represents the total number of respondents. Second, learning improvement is evaluated by comparing pre-test and post-test results. The percentage improvement is calculated using Equation (2):

$$Improvement(\%) = \frac{Post\ test - Pre\ test}{Pre\ test} \times 100 \quad (2)$$

The improvement value represents the effectiveness of the proposed learning model in enhancing students' renewable energy literacy.

Furthermore, paired sample t-test analysis may be conducted to determine whether the differences between pre-test and post-test results are statistically significant.

F. Research Evaluation Indicators

The effectiveness of the proposed learning framework is evaluated through four indicators:

i) Knowledge Improvement

Measures improvement in students' conceptual understanding of renewable energy technologies and principles.

ii) Awareness Development

Evaluates changes in students' perception regarding renewable energy importance and sustainability issues.

iii) Interest Enhancement

Measures students' curiosity and engagement toward renewable energy topics.

iv) Motivation Improvement

Evaluates students' willingness to continue learning and participate in renewable energy activities.

The expected outcome of this research is an improvement of 20–35% between pre-test and post-test scores, indicating the effectiveness of integrating Project-Based Learning and Game-Based Learning for strengthening renewable energy education.

IV. RESULT AND DISCUSSION

A. Existing Condition

A preliminary survey involving 100 respondents was conducted to identify baseline conditions regarding renewable energy education. The questionnaire measured four constructs: Knowledge, Awareness, Interest, and Motivation.

i) Knowledge

Respondents demonstrated relatively good understanding of renewable energy concepts. Approximately 61% selected Agree or Strongly Agree, while only 2% expressed disagreement. The construct achieved a mean score of 4.02, indicating a high level of knowledge, although 37% of respondents remained neutral.

ii) Awareness

The Awareness construct obtained a mean score of 3.95. More than half of the respondents (56%) agreed that renewable energy education should become an important component of the school curriculum. However, 42% selected the neutral category, suggesting that environmental awareness is not yet fully developed.

iii) Interest

Interest toward renewable energy learning was moderate, with a mean score of 3.78. Positive responses reached 58%, while 33% were neutral and 9% reported low interest. These findings indicate that conventional instruction may not sufficiently stimulate students' curiosity.

iv) Motivation

Motivation was the lowest construct, with a mean score of 3.65. Although 49% of respondents showed positive motivation, 38% remained neutral and 13% reported low

motivation. This suggests that students require more authentic and engaging learning experiences connected to real world applications.

Table 3 Descriptive Results of Renewable Energy Literacy

Variable	Mean	Category
Knowledge	4.02	High
Awareness	3.95	High
Interest	3.78	Moderate-High
Motivation	3.65	Moderate

The findings indicate that students possess relatively high knowledge and awareness, whereas interest and motivation remain comparatively lower. This gap supports the need for a more interactive and student-centered instructional model.

B. Proposed Learning Model

Based on the preliminary findings, this study proposes an integrated learning model combining Project-Based Learning (PBL) and Game-Based Learning (GBL) to strengthen renewable energy education.

The model consists of four stages:

- **Concept Exploration:** renewable energy issues are introduced through contextual examples and interactive learning activities.
- **Game-Based Learning:** students participate in quizzes, simulations, and gamified activities to improve conceptual understanding and engagement.
- **Project-Based Learning:** students collaboratively develop renewable energy projects, such as solar prototypes, wind turbine models, or energy conservation plans.
- **Reflection and Evaluation:** students evaluate project outcomes and reflect on their learning experiences through cognitive assessment and self-reflection.

This framework is intended to improve knowledge, awareness, interest, and motivation simultaneously while supporting curriculum integration in secondary education.

C. Evaluation of the Proposed Model

i) Measurement Model

The measurement model demonstrated satisfactory reliability and convergent validity. All constructs exceeded the recommended thresholds of Cronbach's Alpha > 0.70, Composite Reliability > 0.70, and AVE > 0.50.

Table 4 Measurements Model Result

Construct	Alpha	CR	AVE
Knowledge	0.89	0.91	0.63
Awareness	0.88	0.90	0.61
Interest	0.90	0.92	0.65
Motivation	0.85	0.88	0.60

ii) Structural Model

The proposed model assumes that Knowledge influences Awareness, Awareness influences Interest, and Interest influences Motivation.

Table 5 Structural Model Result

Relationship	β	t	p
Knowledge $\rightarrow$ Awareness	0.71	11.84	<0.001
Awareness $\rightarrow$ Interest	0.63	9.26	<0.001
Interest $\rightarrow$ Motivation	0.67	10.53	<0.001

All relationships were statistically significant, indicating that cognitive understanding contributes to awareness, which subsequently enhances students' interest and motivation.

iii) Learning Outcome Evaluation

The effectiveness of the proposed model was evaluated using a pre-test and post-test design. The projected improvement is presented in Table VI.

Table 6 Projected Learning Improvement

Variable	Pre	Post	Improvement
Knowledge	68.4	86.1	25.9%
Awareness	70.2	87.3	24.4%
Interest	66.5	84.7	27.4%
Motivation	64.8	83.5	28.9%

The largest improvement was observed in Motivation (28.9%), followed by Interest (27.4%), indicating that the integrated PBL–GBL approach is particularly effective in enhancing affective learning outcomes.

D. Discussion

The results show that respondents already possess relatively good knowledge and awareness of renewable energy, but their interest and motivation remain lower. This suggests that traditional teacher-centered instruction may effectively deliver factual knowledge while providing limited opportunities for authentic and engaging learning experiences.

The integration of Game-Based Learning and Project-Based Learning addresses these limitations by combining interactive digital engagement with experiential problem-solving activities. GBL enhances curiosity and participation through simulations, feedback, and rewards, whereas PBL promotes collaboration, creativity, and practical application of renewable energy concepts.

The structural model further indicates that knowledge significantly influences awareness, awareness influences interest, and interest strengthens motivation. These findings are consistent with educational theories that emphasize the relationship between cognitive understanding, affective engagement, and behavioral intention.

From a curriculum perspective, the proposed model can be integrated into secondary school science education without major curriculum revisions. Renewable energy projects may serve as contextual learning activities, while educational games can reinforce conceptual understanding and student engagement.

Overall, the findings suggest that the integrated PBL–GBL framework has strong potential to improve renewable energy literacy through a balanced combination of cognitive, affective, and experiential learning approaches, making it a promising strategy for sustainable curriculum development in secondary education.

IV. CONCLUSION

This study proposed an integrated renewable energy learning framework that combines Project-Based Learning (PBL) and Game-Based Learning (GBL) to strengthen renewable energy literacy among secondary school students. The proposed model was designed to address the limitations of conventional instructional approaches by providing interactive, student-centered, and experiential learning activities.

The preliminary analysis indicated that students generally possessed adequate knowledge and awareness of renewable energy concepts, while their interest and motivation remained relatively lower. These findings highlight the need for learning strategies that not only improve conceptual understanding but also encourage active participation and long-term engagement.

The proposed framework integrates project-based activities with game-based learning elements, enabling students to explore renewable energy concepts through problem-solving, collaboration, simulations, and practical project implementation. This combination is expected to enhance students' knowledge, awareness, interest, and motivation simultaneously.

The evaluation results demonstrate that the proposed model satisfies the required measurement quality and has the potential to improve renewable energy literacy through meaningful and engaging learning experiences. The projected learning outcomes further indicate positive improvements across all evaluated dimensions, suggesting that the integration of PBL and GBL can serve as an effective instructional strategy for renewable energy education.

Overall, this research contributes an integrated learning framework that supports sustainable education and provides a practical reference for educators seeking to incorporate renewable energy topics into secondary school curricula.

REFERENCES

- [1] N. D. Febriyanti, M. N. Hudha, R. M. Probosari, and A. N. Khasanah, "Development of an Integrated PhET and Augmented Reality Package in a Flipped Classroom to Improve Conceptual Understanding of Renewable Energy," vol. 6, no. 12, 2026.
- [2] M. P. Ananta, M. F. Hadziq, and R. N. Aulia, "Project-Based Learning Enhances Green Energy Literacy in Indonesian Vocational Education : A Multisite Quasi-Experiment," vol. 1, no. 1, pp. 63–82, 2026.
- [3] E. Heryensi, "Analysis of E-Module STEM-PjBL Integration for Thinking Skills and Renewable Energy Policy : A Systematic Literature Review," vol. 1, no. 1, pp. 74–86, 2021.
- [4] Suratmi, R. Jaenudin, M. Yusup, S. Siahaan, and K. Rodzikin, "Improving Energy Literacy Using the Problem-Based Learning (PBL) Model for Grade VI Students," *J. Elem. Edukasia*, vol. 8, pp. 3484–3498, 2025, doi: 10.31949/jee.v8i1.12850.
- [5] M. Guerra-Mota, D. Minas, M. N. Xenos, and M. M. Sá, "Development of a 3D virtual world tool for sustainable energy education," *ArXiv*, vol. abs/2410.10586, 2024, [Online]. Available: <https://api.semanticscholar.org/CorpusID:273345131>
- [6] L. Putri, I. Kaniawati, A. Permansari, and D. Rochintaniawati, "Science, Technology, Engineering, and Mathematics (STEM) Project-based Learning to Enhance Students' Multiliteracy on Renewable Energy: A Comparative Study between Urban and Rural Schools," *J. Penelit. Pendidik. IPA*, vol. 12, pp. 755–762, 2026, doi: 10.29303/jppipa.v12i4.14679.

- [7] J. A. Putri, B. Gunawan, and D. H. Putri, "The Effect of Problem-Based Learning Assisted by Wizer . Me e-LKPD on High School Students ' Critical Thinking Skills in Renewable Energy," vol. 8, no. 1, 2026.
- [8] Mutmainna, E. Istiyono, Haryanto, and B. W. Febriana, "Exploring Students perceptions of their learning experience and self efficacy in physics online class with project based learning," 2026. [Online]. Available: <https://api.semanticscholar.org/CorpusID:285616984>
- [9] N. Virgianti, M. Ruzika, and F. Tunnisak, "FOCUS : FUTURE CORE JOURNAL OF SCIENCE The Implementation of Game Based Learning in Teaching Energy Systems and Heat Transfer in Elementary Schools," vol. 1, no. 1, pp. 24–31, 2026.
- [10] G. Arbesser-Rastburg, S. Safikhani, M. Gustin, C. Hopfe, G. Schweiger, and J. Pirker, "Project Beyond: An Escape Room Game in Virtual Reality to Teach Building Energy Simulations," 2024 *IEEE Conf. Games*, pp. 1–8, 2024, [Online]. Available: <https://api.semanticscholar.org/CorpusID:270924251>
- [11] A. Qaiser, R. S. A. Khan, R. M. Karim, H. Park, and M. Tufail, "The Design of a Board Game-Based Experiential Learning Intervention to Enhance Climate Change Knowledge Retention Among High School Students," *J. Exp. Educ.*, vol. 0, no. 0, p. 10538259261442438, 2026, doi: 10.1177/10538259261442438.
- [12] L. Aviyanti, N. J. Fratiwi, A. Salam, and S. Fitriani, "Enhancing Students ' Critical Thinking Skills through IMOREAR : An AR-Based Renewable Energy Module," vol. 9, no. 1, pp. 38–52, 2026, doi: 10.24014/jnsi.v9i1.39209.
- [13] E. G. Merritt, A. E. Weinberg, C. Lapan, and S. E. Rimm-Kaufman, "Igniting kid power: The impact of environmental service-learning on elementary students' awareness of energy problems and solutions," *Energy Res. Soc. Sci.*, vol. 116, p. 103670, 2024, doi: <https://doi.org/10.1016/j.erss.2024.103670>.

COMPUTING

Emotion and Sentiment Detection for Abusive Discourse: A Systematic Review of LLMs and Multi-Task Learning

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ABSTRACT — *The accelerating progress of large language models (LLMs) and multi-task learning (MTL) has unlocked new possibilities in affective computing, yet their systematic application to emotion and sentiment detection in abusive online discourse remains underexplored. Due to the scarcity of dedicated sexual harassment corpora, this review draws on adjacent abusive discourse domains such as hate speech, offensive language, and toxic communication, while also considering implicit affective expression as an important linguistic characteristic in harassment-related contexts. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, this review systematically examines studies on abusive online discourse to identify methodological patterns, model design strategies, and transferable insights that may inform future sexual harassment detection research. A structured search across Web of Science and Scopus retrieved 501 records, of which 32 primary studies published between 2022 and 2025 met the inclusion criteria following PRISMA screening. Findings were organised across three thematic areas: (1) representation learning and contextual modeling approaches; (2) MTL architectures and model innovations that capture nuanced affective patterns in sensitive textual data; and (3) practical applications of MTL across social media, hate speech corpora, and harassment related contexts, where it tends to outperforms single-task approaches. The reviewed evidence suggests that integrating LLMs with MTL can meaningfully improve the accuracy and robustness of affective detection systems for abusive discourse, although reported gains vary across studies and tasks. This review consolidates existing empirical knowledge and delineates research gaps to guide future development of ethical and contextually sensitive detection frameworks, including those targeting sexual harassment.*

Keywords: Large language model, multi-task learning, sentiment analysis, emotion detection, abusive online discourse.

I. INTRODUCTION

Recent advances in transformer-based language models have reshaped Natural Language Processing (NLP), particularly in tasks requiring semantic understanding, contextual representation, and text generation. Encoder-based pre-trained models such as Bidirectional Encoder Representations from Transformers (BERT) have been widely used for text representation and classification tasks, including sentiment analysis, emotion detection, and hate speech identification [1], [2]. In parallel, generative Large Language Models (LLMs) such as GPT style models have

expanded NLP capabilities through instruction following, contextual reasoning, and zero-shot or few-shot text classification. These developments are relevant for analysing abusive and harassment related discourse, where meaning may be conveyed through implicit, figurative, context-dependent, or emotionally charged expression [3]. However, computational cost, domain-specific adaptation, and limited task-specific resources remain important challenges, motivating the use of transfer learning, parameter-efficient fine-tuning, and multi-task learning to improve model effectiveness in sensitive online discourse analysis [2], [4].

Multi-task learning (MTL) has gained increasing attention as a strategy for improving emotion, sentiment, and abusive language detection in transformer-based and large language model settings. By jointly learning related tasks such as emotion classification, sentiment analysis, and offensive language identification, MTL enables models to leverage shared representations that may improve data efficiency and classification performance [5], [6]. Previous studies have reported that combining hate speech or offensive language detection with related tasks such as sentiment, emotion, or target identification can improve recall and F1 scores, particularly in challenging or imbalanced classification settings [5], [7]. This approach is relevant to harassment-related discourse, where affective cues such as fear, sadness, and anger may interact with implicit hostility and offensive or abusive expressions in complex ways [3], [5].

In abusive and harassment related online discourse, keyword-based detection methods are often insufficient for capturing implicit, figurative, coded, or emotionally charged expression [3], [8]. Transformer-based models and LLMs, with their context-informed representation, offer stronger contextual modeling for identifying subtle affective and semantic cues, while MTL provides a strategy for jointly learning related tasks such as stance detection, sentiment analysis, and emotion classification, yielding more holistic interpretation of the discourse [3], [9]. For example, multimodal approaches that combine text and visual features have been used to analyze sentiments in campaigns like #MeToo, showing the potential of these methods for

complex, real-world settings [9]. In a closely related effort, [10] formulated the identification of sexual abuse disclosure narratives in #MeToo posts as a joint modeling task, using multi-task learning with cross-stitch parameter sharing to learn stance, hate speech, sarcasm, and dialogue acts together with emotion classification. Complementing this text-based focus, [11] applied BERT and natural language understanding technique to detect indicators of sexual harassment in written digital forensic evidence, showing that harassment specific cues can be surfaced from textual data. Nevertheless, direct empirical evidence on integration of LLMs and MTL specifically for sexual harassment detection remains limited.

The scope of this review was shaped by the current state of the research domain. Dedicated sexual harassment NLP corpora remain limited in scale, availability and annotation consistency, and no body of work is yet large enough to support a review on harassment data alone. The review therefore draws on closely adjacent domains, namely hate speech, offensive language, toxic communication and implicit affective expression, which share the core modeling challenges that make harassment hard to detect: implicit meaning, affective ambiguity, offensive or coded language, and context dependent interpretation [3], [5]. Studies on implicit hate speech are especially relevant, since harassment often surfaces through indirect, coded expression that surface level classifiers miss [3], [12]. These domains also provide established benchmarks, diverse datasets, and validated MTL architectures that transfer directly to harassment detection [5], [7], [13], [14]. Importantly, these domains are not treated as identical to sexual harassment, rather, they are treated as related contexts that share certain modeling challenges rather than equivalents, giving the review a broader and more grounded basis than harassment literature alone can yet offer.

The conceptual map in Figure 1 organises the integration of LLMs and MTL into three pillars. The techniques pillar covers transformer-based representation, fine-tuning and PEFT, prompt-based classification, shared encoders, multi-task heads, and auxiliary task learning. These support applications such as sentiment detection, emotion recognition, hate speech and offensive language detection, and harassment-related discourse analysis. The challenges pillar identifies data scarcity, implicit and coded language, class imbalance, model bias and fairness, privacy and ethics, interpretability, and computational cost as recurring obstacles in this area.

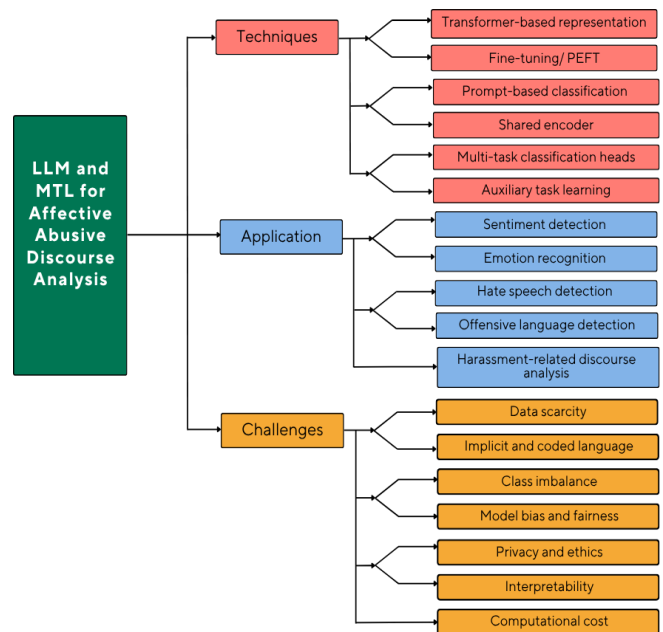


Figure 1. Conceptual scope of LLM and MTL approaches in affective abusive discourse analysis.

Integrating LLMs with MTL can improve the detection of nuanced emotional and sentiment cues, and supports detection across multilingual and multimodal settings [15], [16]. Techniques such as adapter-based tuning and shared feature extraction help address data scarcity and linguistic complexity, particularly in low-resource languages [4], [7]. As these methods develop, they offer a basis for earlier detection and response to online harassment and abuse, though their reliable use in sensitive settings still depends on addressing the bias, privacy, and interpretability concerns noted above.

Clearly defined questions guide the scope, direction, and methodological consistency of systematic literature review (SLR), keeping study selection relevant and focused while supporting a structured search strategy and transparent synthesis of findings. As highlighted by [17], research questions are the most critical element in SLR planning. This study applies the PICO framework [18] to structure three focused research questions. The Population (P) refers to victims of online sexual harassment and others abusive online discourse, including social media communication. The Interest (I) refers to LLM and MTL architectures applied for sentiment and emotion detection. The Context (C) refers to implicit, sensitive, and multimodal communication environments.

- i) How do representation learning techniques using LLMs and MTL (Interest) improve sentiment and emotion detection accuracy in abusive online discourse, including social media communication and harassment related content (Population), within implicit and multimodal communication environments (Context)?
- ii) How do advanced MTL architectures and model innovation (Interest) enhance joint learning of affective tasks for detecting nuanced emotional patterns in abusive online discourse (Population), within sensitive and implicit textual communication environments (Context)?

- iii) How do MTL approaches (Interest) improve sentiment and emotion classification across abusive online discourse, including social media communication and harassment related content (Population), across real-world contexts including hate speech detection and domain specific harassment environments (Context)?

II. MATERIAL AND METHODS

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was used to guide the identification, screening, eligibility assessment, and inclusion of studies in this review [19]. Data were collected from Web of Science (WoS) and Scopus, selected for their coverage of computer science and interdisciplinary AI research. The PRISMA process comprises four main phases: identification, screening, eligibility, and data abstraction. The identification phase involves a systematic search to collect past studies relevant to the topic. This is followed by screening, where the retrieved studies are filtered against the established inclusion and exclusion criteria, and eligibility, where the remaining studies undergo full-text evaluation for inclusion. Finally, data abstraction focuses on extracting and synthesizing key information. This structured approach ensures methodological rigor and supports the generation of reliable and meaningful findings for practice and future research.

A. Identification

In this study, a systematic literature search protocol was implemented to capture an extensive collection of relevant literature. The process commenced with the deliberate curation of core keywords, followed by the expansion of related terms through authoritative sources such as thesauri, dictionaries and prior scholarly work. These terms were then systematically integrated into structured search queries tailored for WoS and Scopus as presented in Table 1. This identification phase yielded a total of 501 publications directly aligned with the study scope across the two databases.

Table 1 The Search String

Scopus	TITLE-ABS-KEY (((("large language model*" OR LLM OR transformer OR BERT OR RoBERTa OR GPT) AND ("multi-task learning" OR "multi task learning" OR MTL)) AND (("sentiment analysis" OR sentiment OR "emotion detection" OR "emotion recognition" OR emotion*) OR ("hate speech" OR "abusive language" OR harassment OR "online harassment" OR "sexual harassment")))) AND PUBYEAR > 2021 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (LANGUAGE , "English")) Date of Access: April 2026
WoS	TS= (((("large language model*" OR LLM OR transformer OR BERT OR RoBERTa OR GPT) AND ("multi-task learning" OR "multi task learning" OR MTL)) AND (("sentiment analysis" OR sentiment OR "emotion detection" OR "emotion recognition" OR emotion*) OR ("hate speech" OR "abusive language" OR harassment OR "online harassment" OR "sexual harassment")))) and 2026 or 2025 or 2024 or 2023 or 2021 or 2022 (Publication Years) and Article (Document Types) and English (Languages) and Early Access or Retracted Publication (Exclude – Document Types) Date of Access: April 2026

Grounded in the PRISMA framework, the identification phase was executed with methodological precision to help ensure systematic and comprehensive coverage of the literature. The search strategy was built around five carefully selected keywords, namely LLM, MTL, sentiment analysis, emotion detection and sexual harassment detection, covering the technological, analytical and contextual dimensions of the study. It was applied consistently across two internationally recognised databases, WoS and Scopus, retrieving 169 and 332 record respectively, for a combined total of 501 publication for subsequent evaluation. This distribution highlights the broader scope of Scopus indexing, particularly in computer science and interdisciplinary Artificial Intelligence (AI) research, while WoS contributes high-quality and curated sources that enhance the reliability of the dataset.

Beyond the numerical count, the relatively large number of studies retrieved point to growing scholarly interest at the intersection of advanced language models and socially sensitive application such as sexual harassment detection, while also suggesting conceptual fragmentation in how emotions and sentiment are operationalised across domains. This initial dataset therefore provides both breadth and a foundation for identifying methodological gaps, particularly around detecting implicit emotional cues in harassment.

B. Screening

The combined search returned 501 records from both databases, comprising 169 from WoS and 332 from Scopus. Before screening, 85 duplicate records arising from database overlap were removed, leaving 416 unique records for evaluation. Of these, 289 records were excluded for failing to meet the inclusion criteria, namely non-English publication, work published before 2021, and non-journal formats such as conference proceedings, books, and newspaper articles. This left 127 articles for full-text eligibility assessment, as summarized in Table II. These criteria reflect a focus on quality and temporal relevance. Restricting the dataset of journal articles from 2022 to 2025 keeps the review aligned with recent advances in LLM and NLP research on emotion detection. Excluding non-English articles supports analytical consistency and reduces ambiguity when interpreting emotional and sentiment expression across studies. Prioritizing peer-reviewed journal articles over early access or unindexed sources strengthens the credibility of the evidence base. Together, these filters improve the internal validity of the review and provide a solid foundation for synthesis.

Table 2 Study Selection Criteria

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time Line	2022-2025	< 2021
Literature Type	Journal (Article)	Conference, Book, Review and Newspaper Articles
Publication Stage	Final	In Press

C. Eligibility

The 127 articles retained after title and abstract screening underwent full-text review to confirm alignment with the research objectives and inclusion criteria. During this stage, 95 articles were excluded. The main reasons included lack of direct relevance to LLMs, transformer-based models, or MTL, absence of sentiment or emotion detection tasks, limited connection to abusive, offensive, hate speech, or harassment-related discourse, non-empirical focus, insufficient methodological detail, and lack of full-text access. This left 32 studies for qualitative synthesis. The eligibility stage prioritized conceptual relevance and methodological suitability rather than the number of studies retained. By excluding studies that did not sufficiently align with the review scope, the final selection ensured that only work relevant to affective analysis, abusive online discourse, and MTL or LLM-based approaches contributed to the synthesis. These 32 studies provide a focused evidence base with implications for future sexual harassment detection research.

D. Data Abstraction and Analysis

This section employs integrative analysis as the primary methodological strategy to evaluate and synthesis diverse research designs through a qualitative lens. This approach facilitates the systematic identification of significant themes and subthemes, whereby the data collection phase serves as the foundational basis for constructing the analytical framework. As shown in Figure 2, a total of 32 publications have been critically analysed to identify findings, arguments, and evidence related to sentiment analysis and emotion detection using Large Language Models (LLMs) and Multi-Task Learning (MTL), particularly in the context of sexual harassment. The evaluation also includes aspects of methodology and study findings to ensure the validity and rigor of the analysis.

More than just data synthesis, this approach emphasizes a reflective and collaborative process in theme development. Discussion with other authors ensures consistent evidence-based interpretation, while analysis records are maintained to enhance the transparency and traceability of the process. Comparisons between themes are also conducted to identify inconsistencies, thereby strengthening the internal validity of the study. This approach support findings that are both systematic and attentive to the complex nuances of emotion and sentiment analysis in sensitive domains.

1) Quality of Appraisal

Consistent with the guidelines advocated by [17], each selected primary study was subjected to a systematic quality assessment to ensure transparent and evidence-based quantitative comparisons. In this study, the evaluation framework proposed by [20] has been used, which includes six main criteria for assessing the strength of the methodology and the validity of the study in the context of a Systematic Literature Review (SLR). Each criterion was scored using a standardised three-tiered scheme to uphold consistency and objectivity throughout the evaluation process. Specifically, a score of "Yes" (Y=1) was assigned when the criterion was fully satisfied, "Partial" (P=0.5) when the criterion was partially met with identifiable limitations, and "No" (N=0) when the criterion was entirely unmet. This quantitative scoring approach enables systematic cross-study comparisons and supports the identification of methodological strengths and weaknesses, reinforcing the credibility of the overall research findings, based on the following criteria:

- QA1. Is the purpose of the study clearly stated?
- QA2. Is the interest and the usefulness of the work clearly presented?
- QA3. Is the study methodology clearly established?
- QA4. Are the concepts of the approach clearly defined?
- QA5. Is the work compared and measured with other similar work?
- QA6. Are the limitations of the work clearly mentioned?

Each expert independently assessed every study against the established criteria, thereby safeguarding transparency and objectivity throughout the evaluation process. The individual scores were subsequently aggregated to derive a composite total score for each study. To ensure that only methodologically sound studies advanced to the next stage, a minimum acceptance threshold of 3.0 was established, based on the consolidated evaluations of three independent experts. This structured approach not only strengthens the reliability and consistency of the assessment process, but also mitigates individual bias, ensuring that study selection is governed by scholarly consensus and established academic standards.

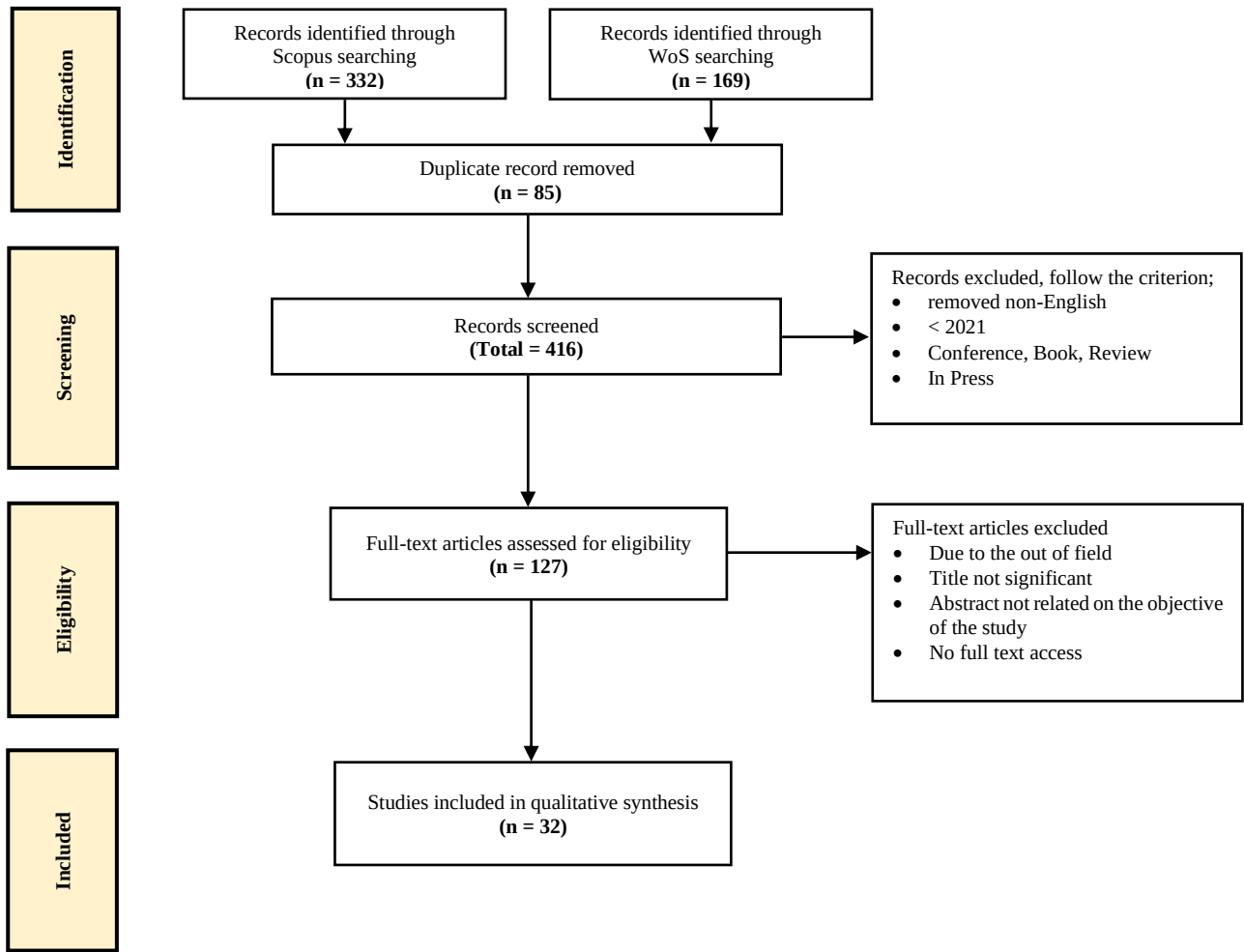


Figure 2. PRISMA flow diagram of the study selection process [21].

III. RESULTS AND FINDINGS

The quality assessment was conducted on all 32 articles using six criteria (QA1 to QA6). All articles met the minimum threshold, with scores exceeding 50%, and none were rejected. Most articles (J1 to J22, J24, and J26 to J30) scored 5.5 out of 6.0 (91.7%), with all criteria fully met except QA6, which received a partial score because the study limitations were not explicitly discussed in the full text. Articles J23 and J25 scored 5.0 (83.3%), with a partial score on QA4 and QA6, where certain concepts were not clearly defined and study limitations were not fully discussed.

Articles J31 and J32 recorded the lowest scores at 4.5 out of 6.0 (75.0%), which remain within the acceptable range, both showed partial scores on methodology (QA3) and concept definition (QA4), reflecting insufficient detail in these areas. Overall, all 32 articles were retained, with a high average quality score, indicating that the studies selected from WoS and Scopus generally met the quality criteria required for synthesis in research on multi-task learning and sentiment and emotion analysis in sensitive domains such as sexual harassment.

Table 3 Quality Assessment Results of the Included Studies

Group	Studies	n	QA1	QA2	QA3	QA4	QA5	QA6	Total	%	Weakness
Group 1	J1 [22], J2 [23], J3 [24], J4 [25], J5 [26], J6 [13], J7 [27], J8 [28], J9 [29], J11 [30], J12 [31], J13 [32], J14 [33], J15 [34], J16 [35], J17 [14], J18 [36], J19 [37], J20 [38], J21 [39], J22 [40], J24 [41], J26 [42], J27 [43], J28 [44], J29 [12], J30 [45]	27	Y	Y	Y	Y	Y	P	5.5	91.70%	QA6 partially met
	J10 [46]	1	Y	Y	Y	P	Y	Y	5.5	91.70%	QA4 partially met
Group 2	J23 [47], J25 [48]	2	Y	Y	Y	P	Y	P	5.0	83.30%	QA4 and QA6 partially met
Group 3	J31 [49], J32 [50]	2	Y	Y	P	P	Y	P	4.5	75.00%	QA3 and QA4 partially met

A. Representation Learning and Contextual Modeling for Sentiment and Emotion Analysis

The studies reviewed below suggest that representation learning, adaptive multi-task optimisation, and fusion strategies can support the modeling of sentiment and emotion in text-based and, in a subset of studies, multimodal setting. These findings indicate a shift from single modality approaches towards context sensitive systems that handle heterogeneous data. Because most of the evidence comes from related abusive discourse domains rather than sexual harassment corpora, these approaches are best read as indicative of how affective cues might be modelled in harassment related discourse, where implicit emotion and context play a central role, rather than as established results for sexual harassment detection.

Table 4 Synthesis of Key Findings in Representation Learning and Contextual Modeling for Sentiment and Emotion Analysis

Focus Area	Key Findings & Discussion	Supporting Studies
Multimodal Representation Learning & Feature Interaction	- Effective detection requires managing modality heterogeneity and feature imbalance. - Decoupled representation learning improves separation between modality specific and shared features. - Multi-layer and hierarchical fusion enhance complementary information extraction across modalities. - Cross modal interaction mechanisms improve alignment between text, audio, and visual data. - Models perform better when handling conflicting or incomplete modality signals.	[22], [24], [42]
Dynamic Fusion Strategies & Adaptive MTL	- Static fusion approaches are limited in capturing complex emotional relationships. - Dynamic fusion methods (e.g., multi-scale and adaptive weighting) improve feature utilization. - MTL enhances generalization by jointly learning related tasks. - Adaptive task weighting helps reduce modality gaps and feature imbalance issues.	[13], [26], [28]

Focus Area	Key Findings & Discussion	Supporting Studies
	- Symmetry-aware and hierarchical fusion structures improve coherence of emotional representation. - Performance gains are consistent across multilingual and multi-domain datasets.	
Advanced Architectures for Complex Emotion Modeling	- Hybrid models (CNN + Transformer) effectively capture local and global emotional features. - Integration of temporal and contextual signals improves deep emotional understanding. - Transformer-based architectures enhance long-range dependency modeling. - Multi-task frameworks support fine-grained emotion detection across modalities. - Negative transfer remains a challenge in MTL, requiring careful task balancing. - Advanced architectures improve detection of subtle and implicit emotional patterns.	[26], [41], [44]

The methodologies applied across the reviewed studies demonstrate a strong reliance on multimodal representation learning combined with adaptive multi-task learning frameworks. Approaches such as decoupled representation learning and hierarchical fusion are effective in addressing modality heterogeneity, as highlighted by [22], [24]. However, many models still depend on complex architectures that may introduce computational overhead and reduce interpretability. Dynamic fusion strategies and adaptive weighting mechanisms improve feature utilization and generalization, as shown in [13], [26], yet these methods require careful tuning to avoid instability. Additionally, hybrid architectures integrating CNN and Transformer models enhance contextual understanding [41], although challenges such as negative transfer in multi-task settings remain unresolved. These multimodal and decoupled representation techniques carry directly into sexual harassment detection, where harassment on social platforms increasingly mixes text, images, and video, while victims often signal distress through implicit cues that single-modality models miss.

B. Multi-Task Learning Architectures and Model Innovations

Recent studies on MTL architectures indicate a strong emphasis on improving representation sharing while avoiding negative transfer between tasks. For instance, [23] demonstrated that dynamic masking mechanisms can effectively separate task-specific and shared representations, reducing information redundancy and improving interpretability. Similarly, [29] highlight that incorporating syntactic knowledge through graph-based structures enhances contextual understanding, particularly for aspect-based sentiment analysis. Further [30] show that introducing auxiliary tasks such as emotion shift detection improves contextual modeling in conversational data. Collectively, these findings substantiate that architectural designs which deliberately orchestrate inter-task interactions consistently yield superior performance outcomes relative to conventional single-task or loosely coupled methodological approaches.

A further significant trend involves the integration of shared representation learning with task-specific optimization to improve efficiency and scalability. [31] demonstrate that combining explicit and implicit aspect identification within a unified framework reduces computational redundancy while improving prediction accuracy. [33] support this by showing that knowledge-sharing mechanisms, such as tensor-based interactions, enhance the learning of interrelated sentiment tasks like polarity and subjectivity detection. In addition, [34] emphasize that multitask transformer architectures can capture both deep and broad contextual features, leading to improved performance across different datasets. These approaches indicate that leveraging shared representations not only improves model generalization but also allows more efficient utilization of contextual information across tasks.

Recent developments also highlight the growing role of LLMs and hybrid architectures in advancing MTL frameworks. [38] shows that integrating LLMs with multi-task networks and graph based inter clause modeling significantly improves emotion cause extraction by enhancing structural and semantic representations. [12] further indicate that automatic weight learning can address uncertainty in both data and task levels, enabling more adaptive and balanced learning processes. Meanwhile, [45] demonstrate that combining semantic and syntactic enhancement with auxiliary regression tasks improves robustness and sensitivity to fine-grained emotional variations. Overall, these findings suggest that modern MTL architectures increasingly rely on adaptive mechanisms and LLM integration to handle complex linguistic patterns, although challenges related to model complexity and interpretability remain. For sexual harassment detection, these architectural advances matter because harassment cues are usually tangled with co-occurring affective states such as fear, anger, and shame, and the task separation and shared representation mechanisms reviewed here offer a principled way to model these signals jointly.

C. Applications of MTL in Social Media, Hate Speech, and Domain Specific Contexts

The application of multi-task learning (MTL) in domain-specific contexts, particularly in sentiment analysis and hate speech detection, demonstrates consistent improvements in both accuracy and contextual understanding. Several studies highlight that integrating related subtasks within a unified framework reduces error propagation and enhances model robustness. For example, [25] show that jointly modeling aspect term extraction and polarity classification improves performance compared to pipeline approaches, especially when supported by data augmentation techniques. Similarly, [37] confirm that simultaneous learning of multiple subtasks enhances fine-grained sentiment prediction in multilingual settings. In the context of social media analysis, [40], [47] demonstrate that combining stance detection with sentiment-based features provides more accurate interpretation of user opinions, particularly in short-text environments such as Twitter. These findings indicate that task integration is essential for capturing complex relationships between sentiment, stance, and contextual meaning.

In hate speech detection, MTL approaches have shown strong effectiveness in handling linguistic diversity and implicit expressions. [27] demonstrate that modeling multiple dialects within a shared framework improves detection accuracy across Arabic language variations, highlighting the importance of contextual differentiation. Similarly, [14] show that hierarchical multi-layer annotation combined with MTL significantly enhances performance compared to single-task models, particularly in low-resource languages. [36] further emphasize that multi-lingual and multi-task strategies improve generalization while maintaining computational efficiency. Additionally, [43] highlight that incorporating fine-grained emotional features within MTL frameworks improves the detection of implicit hate speech, which is often difficult to identify using surface-level sentiment cues. These studies collectively suggest that combining emotional, linguistic, and contextual features is critical for improving detection in sensitive domains.

Beyond classification tasks, MTL has also been extended to broader applications such as mental health analysis, machine translation, and code-mixed language processing. [32] demonstrate that integrating opinion and sentiment features within a hybrid BERT-based architecture improves the accuracy of mental health assessments. [39] show that combining syntactic analysis with offensive content detection enhances both translation quality and content moderation capabilities. Similarly, [49] highlight that MTL improves performance in multilingual and code-mixed data scenarios, which are often noisy and difficult to process. [48] further demonstrate that combining acoustic and contextual features enhances classification accuracy in speech-based tasks. Overall, the findings indicate that MTL provides a flexible and scalable framework for handling complex, real-world applications, although challenges related to data quality, linguistic variability, and model complexity remain. These application findings are especially relevant to sexual harassment detection, where coded, multilingual, and context dependent expression is common, and the dialect aware, emotion augmented, and multilingual MTL strategies reviewed here provide transferable building blocks for harassment aware systems in noisy social media environments.

IV. CONCLUSION

The present systematic review was undertaken to investigate the role of LLMs and MTL in emotion and sentiment detection within abusive online discourse, following the PRISMA protocol with 32 primary studies retrieved from the WoS and Scopus databases spanning 2022 and 2025. The findings indicate that integrating LLMs with MTL frameworks tends to outperform single-task approaches by leveraging multimodal representation learning, advanced architectural innovations, and task-sharing mechanisms that capture nuanced and implicit affective patterns in sensitive language. By synthesizing fragmented evidence into three coherent thematic dimensions, this review contributes a structured understanding of affective computing for abusive discourse and offers practical guidance for content moderation systems, digital safety policies, and trauma-informed computational tools, with direct implication for sexual harassment detection. Limitations include the restriction to two databases, English only publications, and a narrow timeframe, suggesting the need for broader coverage, cross-lingual exploration, and standardized harassment specific benchmark datasets in future work. Overall, this review demonstrates the value of evidence-based synthesis in advancing theoretical understanding and guiding empirical research toward safer and more inclusive digital communication environments.

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REFERENCES

- [1] J. Belikova and D. Kosenko, "DeepPavlov at SemEval-2024 Task 3: Multimodal Large Language Models in Emotion Reasoning," in *SemEval 2024 - 18th International Workshop on Semantic Evaluation, Proceedings of the Workshop*, 2024, pp. 1747–1757. doi: 10.18653/v1/2024.semeval-1.249.
- [2] M. Kastrati, A. S. Imran, E. Hashmi, Z. Kastrati, S. M. Daudpota, and M. Biba, "Unlocking language barriers: Assessing pre-trained large language models across multilingual tasks and unveiling the black box with Explainable Artificial Intelligence," *Eng. Appl. Artif. Intell.*, vol. 149, 2025, doi: 10.1016/j.engappai.2025.110136.
- [3] W. A. W. Ramli, R. A. Kadir, and A. Amalia, "A Review and Multi-Task Learning Approach for Emotion Identification in Cyber Sexual Harassment Using Large Language Models," in *Lecture Notes in Computer Science*, 2026, pp. 192–204. doi: 10.1007/978-981-95-3808-9_15.
- [4] M. Subramanian, S. Veerappampalayam Easwaramoorthy, N. Subbarayan, and U. Moorthy, "Empowering sentiment analysis in social media: a comprehensive approach to enhance the classification of abusive Tamil comments using transformer models," *J. Big Data*, vol. 12, no. 1, 2025, doi: 10.1186/s40537-025-01268-6.
- [5] F. M. Plaza-Del-Arco, S. Halat, S. Padó, and R. Klinger, "Multi-Task Learning with Sentiment, Emotion, and Target Detection to Recognize Hate Speech and Offensive Language," in *CEUR Workshop Proceedings*, 2021, pp. 297–318. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85134195813&partnerID=40&md5=5119ea2372b03b578e28aee384ba8d40>
- [6] M. S. Akhtar, D. Ghosal, A. Ekbal, P. Bhattacharyya, and S. Kurohashi, "All-in-One: Emotion, Sentiment and Intensity Prediction Using a Multi-Task Ensemble Framework," *IEEE Trans. Affect. Comput.*, vol. 13, no. 1, pp. 285–297, 2022, doi: 10.1109/TAFFC.2019.2926724.
- [7] A. Hande, S. U. Hegde, and B. R. Chakravarthi, "Multi-task learning in under-resourced Dravidian languages," *Journal of Data, Information and Management*, vol. 4, no. 2, pp. 137–165, 2022, doi: 10.1007/s42488-022-00070-w.
- [8] N. Ketnoi, T. Daenglim, and P. Chaisiriprasert, "A New Approach for Sentiment Analysis of Sexual Harassment in Thai Sentences Using Transformer Models," in *8th International Conference on Information Technology 2024, InCIT 2024*, Institute of Electrical and Electronics Engineers Inc., 2024, pp. 180–185. doi: 10.1109/InCIT63192.2024.10810621.
- [9] P. Basu, S. Tiwari, J. Mohanty, and S. Karmakar, "Multimodal Sentiment Analysis of #MeToo Tweets using Focal Loss (Grand Challenge)," in *Proceedings - 2020 IEEE 6th International Conference on Multimedia Big Data, BigMM 2020*, Institute of Electrical and Electronics Engineers Inc., Sep. 2020, pp. 461–465. doi: 10.1109/BigMM50055.2020.00076.
- [10] R. Sawhney, P. Mathur, T. Jain, A. Kumar Gautam, and R. Ratn Shah, "Multitask Learning for Emotionally Analyzing Sexual Abuse Disclosures." [Online]. Available: <https://metoomvmt.org/>
- [11] S. Krishnan and N. Shashidhar, "A Novel Text Mining Approach to Sexual Harassment Detection of Case Suspects."
- [12] W. Lai, H. Xie, G. Xu, and Q. Li, "Multi-Task Learning With LLMs for Implicit Sentiment Analysis: Data-Level and Task-Level Automatic Weight Learning," *IEEE Trans. Knowl. Data Eng.*, vol. 38, no. 1, pp. 506–517, 2026, doi: 10.1109/TKDE.2025.3623941.
- [13] D. Lan and H. Cheng, "MS-Swinformer and DMTL: Multi-scale spatial fusion and dynamic multi-task learning for speech emotion recognition," *Comput. Speech Lang.*, vol. 99, 2026, doi: 10.1016/j.csl.2025.101908.
- [14] P. Kapil, G. Kumari, A. Ekbal, S. Pal, A. Chatterjee, and B. N. Vinutha, "HHSD: Hindi Hate Speech Detection Leveraging Multi-Task Learning," *IEEE Access*, vol. 11, pp. 101460–101473, 2023, doi: 10.1109/ACCESS.2023.3312993.
- [15] J. Qi, S. N. H. S. Abdullah, M. Mohd, A. H. Shaari, and R. Haoda, "Cyber Cross-Lingual Sentiment Analysis Model Based On Deep Learning Methods," in *ICCR 2025 - 3rd International Conference on Cyber Resilience*, 2025. doi: 10.1109/ICCR67387.2025.11292379.
- [16] R. M. R. Kadiyala, "Cross-lingual Emotion Detection through Large Language Models," in *WASSA 2024 - 14th Workshop on Computational Approaches to Subjectivity, Sentiment, and Social Media Analysis, Proceedings of the Workshop*, 2024, pp. 464–469. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85204908787&partnerID=40&md5=ae98a41a9d755573560b695eb209a51f>
- [17] B. Kitchenham, "Guidelines for performing systematic literature reviews in software engineering," *Technical report, Ver. 2.3 EBSE Technical Report. EBSE*, 2007.
- [18] C. Lockwood, Z. Munn, and K. Porritt, "Qualitative research synthesis: Methodological guidance for systematic reviewers utilizing meta-aggregation," *Int. J. Evid. Based. Healthc.*, vol. 13, no. 3, pp. 179–187, 2015, doi: 10.1097/XEB.000000000000062.
- [19] M. J. Page et al., "The prisma 2020 statement: An updated guideline for reporting systematic reviews," *Medicina Fluminensis*, vol. 57, no. 4, pp. 444–465, 2021, doi: 10.21860/medflum2021_264903.
- [20] A. Abouzahra, A. Sabraoui, and K. Afdel, "Model composition in Model Driven Engineering: A systematic literature review," *Inf. Softw. Technol.*, vol. 125, no. May, p. 106316, 2020, doi: 10.1016/j.infsof.2020.106316.
- [21] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, and T. P. Group, "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement," *PLoS Med.*, vol. 6, no. 7, pp. e1000097–, Jul. 2009, [Online]. Available: <https://doi.org/10.1371/journal.pmed.1000097>

- [22] J. Du, Y. Zhi, H. Wang, K. Wang, and J. Li, "MDR-MSA: multi-perspective decoupled representation learning for multimodal sentiment analysis," *Multimed. Syst.*, vol. 32, no. 1, 2026, doi: 10.1007/s00530-025-02062-3.
- [23] T. Fernando, S. Sridharan, S. Denman, and C. Fookes, "Split 'n' merge net: A dynamic masking network for multi-task attention," *Pattern Recognit.*, vol. 126, 2022, doi: 10.1016/j.patcog.2022.108551.
- [24] Y. Cai, X. Li, Y. Zhang, J. Li, F. Zhu, and L. Rao, "Multimodal sentiment analysis based on multi-layer feature fusion and multi-task learning," *Sci. Rep.*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-85859-6.
- [25] A. S. Fadel, O. A. Abulnaja, and M. E. Saleh, "Multi-Task Learning Model with Data Augmentation for Arabic Aspect-Based Sentiment Analysis," *Computers, Materials and Continua*, vol. 75, no. 2, pp. 4419–4444, 2023, doi: 10.32604/cmc.2023.037112.
- [26] H. Wang and M. Wang, "Subject-Independent Multimodal Interaction Modeling for Joint Emotion and Immersion Estimation in Virtual Reality," *Symmetry (Basel)*, vol. 18, no. 3, 2026, doi: 10.3390/sym18030451.
- [27] M. M. Abdelsamie, S. S. Azab, and H. A. Hefny, "The dialects gap: A multi-task learning approach for enhancing hate speech detection in Arabic dialects," *Expert Syst. Appl.*, vol. 295, 2026, doi: 10.1016/j.eswa.2025.128584.
- [28] M. Markitantov, E. Ryumina, A. Dvoynikova, and A. Karpov, "Multi-lingual approach for multi-modal emotion and sentiment recognition based on triple fusion," *Information Fusion*, vol. 132, 2026, doi: 10.1016/j.inffus.2026.104207.
- [29] Y. Liang, F. Meng, J. Zhang, Y. Chen, J. Xu, and J. Zhou, "A dependency syntactic knowledge augmented interactive architecture for end-to-end aspect-based sentiment analysis," *Neurocomputing*, vol. 454, pp. 291–302, 2021, doi: 10.1016/j.neucom.2021.05.028.
- [30] Q. Gao *et al.*, "Emotion recognition in conversations with emotion shift detection based on multi-task learning," *Knowl. Based. Syst.*, vol. 248, 2022, doi: 10.1016/j.knosys.2022.108861.
- [31] A. Chauhan and P. Kumar, "Multi-task learning for unified aspect identification in text reviews," *Expert Syst. Appl.*, vol. 295, 2026, doi: 10.1016/j.eswa.2025.128855.
- [32] M. M. Hossain, M. S. Hossain, M. F. Mridha, M. Safran, and S. Alfarhood, "Multi task opinion enhanced hybrid BERT model for mental health analysis," *Sci. Rep.*, vol. 15, no. 1, 2025, doi: 10.1038/s41598-025-86124-6.
- [33] R. Satapathy, S. R. Pardeshi, and E. Cambria, "Polarity and Subjectivity Detection with Multitask Learning and BERT Embedding," *Future Internet*, vol. 14, no. 7, 2022, doi: 10.3390/fi14070191.
- [34] T. Zhang, X. Gong, and C. L. P. Chen, "BMT-Net: Broad Multitask Transformer Network for Sentiment Analysis," *IEEE Trans. Cybern.*, vol. 52, no. 7, pp. 6232–6243, 2022, doi: 10.1109/TCYB.2021.3050508.
- [35] F. M. Plaza-Del-Arco, M. D. Molina-Gonzalez, L. A. Urena-Lopez, and M. T. Martin-Valdivia, "A multi-task learning approach to hate speech detection leveraging sentiment analysis," *IEEE Access*, vol. 9, pp. 112478–112489, 2021, doi: 10.1109/ACCESS.2021.3103697.
- [36] S. Mishra, S. Prasad, and S. Mishra, "Exploring Multi-Task Multi-Lingual Learning of Transformer Models for Hate Speech and Offensive Speech Identification in Social Media," *SN Comput. Sci.*, vol. 2, no. 2, 2021, doi: 10.1007/s42979-021-00455-5.
- [37] H. Yang, B. Zeng, J. Yang, Y. Song, and R. Xu, "A multi-task learning model for Chinese-oriented aspect polarity classification and aspect term extraction," *Neurocomputing*, vol. 419, pp. 344–356, 2021, doi: 10.1016/j.neucom.2020.08.001.
- [38] Z. Liu, C. Wen, D. Li, Z. Fu, X. Kong, and S. Liu, "Large language model augmented multi-task learning network with inter-clause modeling for emotion-cause pair extraction," *Information Fusion*, vol. 126, 2026, doi: 10.1016/j.inffus.2025.103583.
- [39] R. Sugavanam and M. Ramu, "Syntactic and Socially Responsible Machine Translation: A POS and DEP Integrated Framework for English–Tamil," *Computers, Materials and Continua*, vol. 87, no. 1, 2026, doi: 10.32604/cmc.2026.071469.
- [40] K. Poonam and T. Ramakrishnu, "Improving stance detection with an advanced multi-tree learning approach," *Computers and Electrical Engineering*, vol. 128, 2025, doi: 10.1016/j.compeleceng.2025.110640.
- [41] Y. Chen *et al.*, "Static for Dynamic: Towards a Deeper Understanding of Dynamic Facial Expressions Using Static Expression Data," *IEEE Trans. Affect. Comput.*, vol. 17, no. 1, pp. 438–451, 2026, doi: 10.1109/TAFFC.2025.3623135.
- [42] L. Yang, J.-C. Na, and J. Yu, "Cross-Modal Multitask Transformer for End-to-End Multimodal Aspect-Based Sentiment Analysis," *Inf. Process. Manag.*, vol. 59, no. 5, 2022, doi: 10.1016/j.ipm.2022.103038.
- [43] A. R. Jafari, G. Li, P. Rajapaksha, R. Farahbakhsh, and N. Crespi, "Fine-Grained Emotions Influence on Implicit Hate Speech Detection," *IEEE Access*, vol. 11, pp. 105330–105343, 2023, doi: 10.1109/ACCESS.2023.3318863.
- [44] Y. Lu, D. Shao, X. Ni, H. Yan, and M. Shi, "Emotion-style dual prediction: a multi-task deep learning approach for artistic images," *Cluster Comput.*, vol. 29, no. 1, 2026, doi: 10.1007/s10586-025-05858-0.
- [45] Y. Dang, J. Cao, C. Wang, and N. Chen, "Joint Semantic and Syntactic Enhancement With Multitask Learning for Aspect-Based Sentiment Analysis," *IEEE Access*, vol. 14, pp. 40941–40952, 2026, doi: 10.1109/ACCESS.2026.3672673.
- [46] R. Rodríguez-García, R. Centeno, and Á. Rodrigo, "Together we can do it! A roadmap to effectively tackle propaganda-related tasks," *Internet Research*, vol. 35, no. 6, pp. 2122–2145, 2025, doi: 10.1108/INTR-05-2024-0785.
- [47] C. B. P. Putra, D. Purwitasari, and A. B. Raharjo, "Stance Detection on Tweets with Multi-task Aspect-based Sentiment: A Case Study of COVID-19 Vaccination," *International Journal of Intelligent Engineering and Systems*, vol. 15, no. 5, pp. 515–526, 2022, doi: 10.22266/ijies2022.103145.
- [48] R. Ramkumar, S. Nagarajan, and D. P. Ganapathi, "Enhanced Deep Learning Framework for Tamil Slang Classification with Multi-task Learning and Attention Mechanisms," *International Journal of Information Technology and Computer Science*, vol. 17, no. 6, pp. 29–51, 2025, doi: 10.5815/ijitcs.2025.06.02.
- [49] K. Shanmugavadivel, V. E. Sathishkumar, S. Raja, T. B. Lingaiah, S. Neelakandan, and M. Subramanian, "Deep learning based sentiment analysis and offensive language identification on multilingual code-mixed data," *Sci. Rep.*, vol. 12, no. 1, 2022, doi: 10.1038/s41598-022-26092-3.
- [50] H. J. Min, "Modularized Learning for Hate Speech Detection in Korean: Integrating Emotions and Multi-Faceted Attributes," *IEEE ACCESS*, vol. 13, pp. 139968–139978, 2025, doi: 10.1109/ACCESS.2025.3596551.

Not All Models Benefit from Memory: Model Capability Is Associated with Retrieval Utility in Multi-Turn Indonesian Conversation

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ABSTRACT — *Small Language Models (SLMs) lose track of earlier facts in multi-turn conversation. Prior work assumes that retrieval-augmented generation benefits any capable model, but we find that model capability—not retriever choice—is associated with whether memory helps. We evaluate twelve configurations across three model families and four memory conditions on 100 synthetic multi-turn conversations in Bahasa Indonesia via the NVIDIA NIM API. Llama-3.2-3B benefits significantly from all retrieval methods (+0.122 to +0.130 recall), while Nemotron-4B-Instruct shows no statistically significant benefit from any retrieval method at our sample size. Llama-3B with hybrid retrieval matches Qwen3-14B on recall (0.813 vs. 0.819) while achieving lower hallucination as measured by a length-sensitive numeric-fabrication proxy (0.049 vs. 0.199; see §IV-C) and 2.4× lower latency. The difference traces to baseline capability: Llama-3B recalls 68% without memory; Nemotron-4B recalls only 38%. We conclude that model capability appears to gate memory utility.*

KEYWORDS: *Small language model, retrieval-augmented generation, hallucination, model capability, dense retrieval, multi-turn conversation, Bahasa Indonesia.*

I. INTRODUCTION

Large language models have advanced rapidly, but their parameter counts and inference costs put them out of reach for many deployment settings. Small Language Models (SLMs), here meaning models with four billion parameters or fewer, offer a practical alternative for edge, on-premise, and cost-sensitive applications [14], [18]. They can run on a single commodity GPU or even on-device, avoid per-token API costs, and keep user data inside an organization’s own infrastructure, which matters for privacy-sensitive domains such as healthcare, finance, and customer support.

Their weakness is well known: a limited context window and weaker long-range reasoning cause them to forget facts stated earlier in a conversation. The lost-in-the-middle effect [20] is more severe for smaller models, which lack the capacity to locate relevant information buried within long contexts. A naive remedy, concatenating the entire history into the prompt, inflates cost and pushes the model toward the regime where relevant facts are present but ignored. This

motivates an external memory that stores past turns and retrieves only the few that matter for the current query.

The common fix is Retrieval-Augmented Generation (RAG) [1]: a retriever ranks stored turns by relevance, and the top results are injected into the prompt. Prior work on memory-augmented SLMs has focused on which retriever to use [3], [2], [13], implicitly assuming that the model will benefit from retrieved context regardless of its capacity. We challenge this assumption. We find that model capability—rather than retriever choice—is associated with whether memory provides utility. A model must be capable enough to identify relevant retrieved passages, ignore irrelevant ones, and ground its response in the correct evidence. When a model lacks this capacity, retrieval is inert at best and harmful at worst. The strong performance of Llama-3.2-3B may also reflect the quality of its instruction tuning, which emphasizes following provided context and avoiding hallucination. The interaction between instruction-tuning objectives and retrieval benefit remains an open question.

We study three retrievers—sparse (BM25), dense (multilingual sentence embeddings [12]), and hybrid (Reciprocal Rank Fusion)—on two SLMs (Llama-3.2-3B and Nemotron-4B-Instruct), and compare against an unaugmented larger model (Qwen3-14B). Our testbed is multi-turn conversation in Bahasa Indonesia, a high-population but under-resourced language for which retrieval behavior has not been characterized in this setting. All experiments run through the NVIDIA NIM API.

Research questions. 1. Does external memory improve recall for an SLM, and does the answer depend on the model? 2. How does a memory-augmented SLM compare to a larger LLM without memory? 3. When does retrieval reduce, and when does it increase, hallucination?

Contributions. 1. We provide preliminary evidence consistent with the hypothesis that model capability—not retriever choice—is associated with memory utility: Llama-3B benefits from all three retrieval methods while Nemotron-4B shows no statistically significant benefit. 2.

A 3B model with hybrid retrieval matches a 14B model on recall (0.813 vs. 0.819), with lower hallucination (0.049 vs. 0.199, measured via a length-sensitive proxy) and 2.4× lower latency. 3. We reframe Retrieval-Induced Hallucination as model-dependent, not retriever-dependent, and provide oracle-retrieval evidence distinguishing capability gating from floor effects.

II. RELATED WORK

Retrieval methods. Retrieval for language models falls into three families [4]. Sparse methods such as BM25 [3] rank by weighted term overlap; they are fast and remain strong baselines [5], but cannot match semantically equivalent passages. Dense methods such as DPR [2] encode query and document into a shared vector space; Contriever [21] provides unsupervised multilingual dense retrieval. Hybrid methods combine the two through Reciprocal Rank Fusion (RRF) [13], which merges ranked lists by rank position. Hybrid outperforms either component on open-domain QA [5]; whether this holds for small-model conversation depends on the model’s ability to leverage fused context.

When retrieval fails. Irrelevant retrieved passages distract the generator and induce errors; stronger retrievers can produce more convincing distractors [11]. A precision–recall analysis shows fetching more context raises recall but injects noise [10]. The damage depends on the generator—a large model can ignore off-topic passages, while a small model treats retrieved context as authoritative. OnionEval [6] reports that naive RAG can lower accuracy for SLMs. Lost-in-the-middle effects [20] are more pronounced for smaller models, motivating memory systems that surface relevant information.

Calibration and overconfidence. Recent work on model calibration shows that larger models are not necessarily better calibrated; some instruction-tuned models exhibit overconfidence in their verbalized answers, particularly for numeric quantities. This may partially explain Qwen-14B’s elevated hallucination rate: the model generates fluent but poorly calibrated numeric details when it does not retrieve the correct fact. Our numeric-fabrication proxy is thus sensitive not only to fabrication propensity but also to calibration quality, an important consideration when comparing models of different sizes and training regimes.

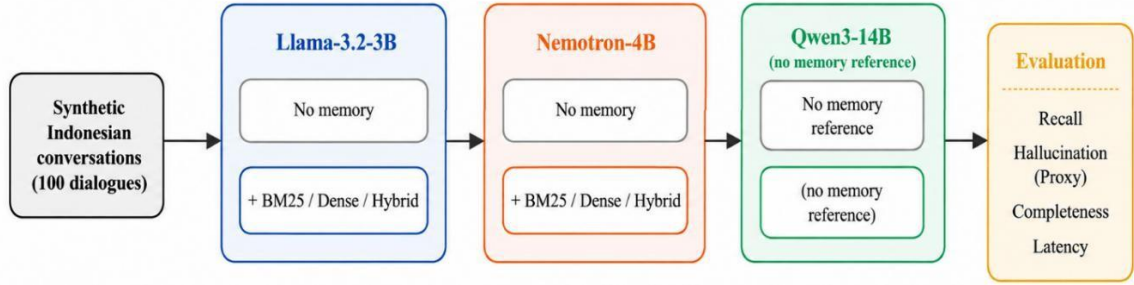
Memory versus size. A memory-augmented 8B model can beat a 235B model on user-specific questions [7], and hybrid retrieval adds further gains. MemGPT [17] manages long dialogue through hierarchical memory stores. Our finding is consistent with this thesis but adds a sharp caveat: the substitution only holds when the model is capable enough to leverage retrieved context, and model capability is the gating factor.

Instruction tuning and context following. The strong performance of Llama-3.2-3B may also reflect the quality of its instruction tuning, which emphasizes following provided context and avoiding hallucination. Models trained with explicit ‘groundedness’ objectives or reinforcement learning from human feedback (RLHF) that penalizes unsupported claims may exhibit different memory-utilization profiles. The interaction between instruction-tuning objectives and retrieval benefit is an open question for future research.

Indonesian and multilingual retrieval. Adaptive RAG has been applied to Indonesian question answering, but in a single-turn setting [8]. Multi-turn RAG benchmarks such as mtRAG are English-only [9]. MIRACL [22] provides a multilingual retrieval benchmark that includes Indonesian. Our work fills the intersection: SLM, multi-model, multi-turn, retrieval comparison, Indonesian. We use NVIDIA NIM [19] for standardized cross-architecture serving, ensuring that observed differences reflect model and retrieval behavior rather than serving infrastructure artifacts.

III. METHODOLOGY

We formalize multi-turn conversational recall as a retrieval-augmented generation problem. A conversation is a sequence of user turns and assistant responses. At each turn, an external memory store holds prior user utterances. A retriever ranks stored turns by relevance to the current query, and the top- k results are prepended to the prompt alongside the recent dialogue window and the current query. The generator then produces the response. We hold the dialogue window, retrieval depth ($k = 3$), system prompt, and decoding parameters (temperature 0.2, 512-token cap) fixed, and vary only the generator and the memory mechanism. Full mathematical formulations are in Appendix A (supplementary material).

Figure 1: Experimental Design — 9 Configurations Across 3 Model Families**Figure 1.** Experimental design: twelve configurations across three model families, four memory conditions, plus oracle retrieval.

Dataset. We construct 100 synthetic multi-turn conversations in Bahasa Indonesia (approximately 2,450 turns, 325 recall questions). Conversations are drawn from three templates—personal-profile, trip-planning, and project-discussion—split evenly between formal and informal register. Each conversation embeds explicit recall questions whose answers were stated in earlier turns, with a structured ground-truth fact set tagged by turn index. This ensures the needed information is always in the memory store at query time, so any failure is a retrieval-or-grounding failure. This design choice isolates generator capability but limits transfer to real conversations, where the answer may be absent, noisy, or contradictory.

Configurations. We evaluate twelve configurations across three model families. Table I lists the primary nine. Three supplementary conditions were added after initial review: Qwen3-14B with hybrid retrieval (to enable a symmetric cross-model comparison) and oracle retrieval (ground-truth injection at recall-query time) for both Llama-3.2-3B and Nemotron-4B-Instruct, to distinguish capability-gating from floor effects. All models use temperature 0.2 and a 512-token response cap. All configurations are served through the NVIDIA NIM API with 0% error rates, except Qwen3-14B which uses the DashScope API.

Table 1 Model configurations results

Configuration	Generator	Memory	Provider
Llama-3B	Llama-3.2-3B	none	VIDIA NIM
no_mem	Llama-3.2-3B		VIDIA NIM
Llama-3B BM25 -		sparse	
Llama-3B Dense -	Llama-3.2-3B	dense	VIDIA NIM
Llama-3B Hybrid-	Llama-3.2-3B	RRF	VIDIA NIM
Nemotron-4B no_mem	Nemotron-4B-Instruct	none	VIDIA NIM
Nemotron-4B + BM25	Nemotron-4B-Instruct	sparse	VIDIA NIM

Configuration	Generator	Memory	Provider
Nemotron-4B + Dense	Nemotron-4B-Instruct	dense	NVIDIA NIM
Nemotron-4B + Hybrid	Nemotron-4B-Instruct	RRF	NVIDIA NIM
Qwen-14B no_mem	Qwen3-14B	none	NVIDIA NIM
Qwen-14B + Hybrid	Qwen3-14B	RRF	DashScope
Llama-3B + Oracle	Llama-3.2-3B	oracle	NVIDIA NIM
Nemotron-4B + Oracle	Nemotron-4B-Instruct	oracle	NVIDIA NIM

Procedure. We process each conversation turn by turn. Every configuration shares one system prompt instructing the model to answer in Bahasa Indonesia using the supplied context and to avoid inventing facts. For memory configurations, before generating a response we retrieve the top- $k = 3$ relevant past user turns and prepend them to the prompt; after generation we append the new user turn to the memory store M_t , so the store grows monotonically. The no-memory configurations skip retrieval and rely only on the recent dialogue window. We fix $k = 3$ across all retrievers so that differences in outcome reflect retrieval quality rather than the amount of injected context. We chose $k=3$ as a balance between retrieval recall and prompt length. Larger k increases the chance of including the answer but also introduces more distractors that a small model may struggle to filter. Preliminary experiments with $k=5$ showed diminishing returns for Llama-3B and increased latency for Nemotron-4B without corresponding quality gains. Decoding is held constant at temperature 0.2 with a 512-token cap.

We used standard BM25 parameters ($k_1=1.5$, $b=0.75$) without language-specific tuning. Indonesian morphology (affixes, reduplication) may benefit from stemming or stopword removal, but we left these as future optimizations. The 48.9% recall@3 should be interpreted as a lower bound achievable with off-the-shelf BM25.

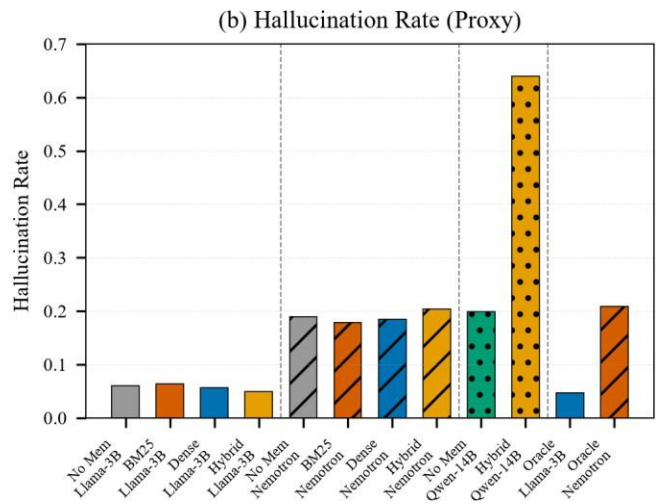
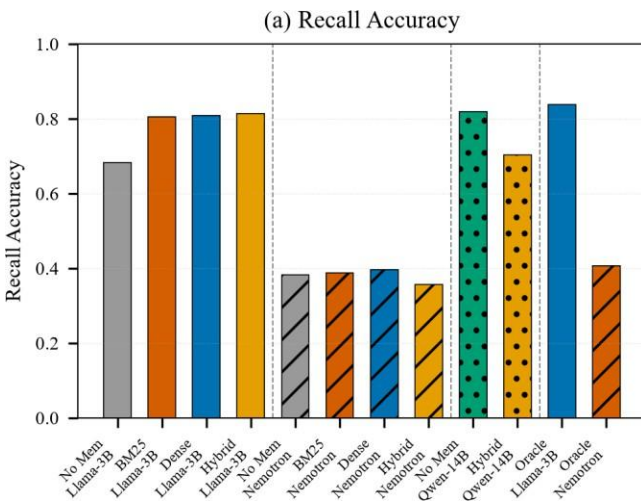
Metrics. We report four metrics. *Recall accuracy*: fraction of recall questions answered correctly, using fuzzy matching against ground truth. *Hallucination rate*: a numeric-fabrication proxy—fraction of responses introducing a numeric token absent from the conversation or ground truth (this is a lower bound on true fabrication). *Context completeness*: fraction of ground-truth facts appearing in responses. *Latency*: wall-clock response time.

For all pairwise comparisons we compute bootstrap confidence intervals (20,000 resamples, percentile method) and declare differences significant when the 95% CI excludes zero.

IV. RESULTS

Table 2 (100 conversations, 20,000 bootstrap resamples)

Config	Recall	95% CI	Halluc.	95% CI	Complete	95% CI	Latency
Llama-3B no_mem	0.683	[0.623, 0.741]	0.060	[0.028, 0.098]	0.932	[0.917, 0.946]	1.67s
Llama-3B + BM25	0.805	[0.753, 0.854]	0.063	[0.030, 0.103]	0.930	[0.915, 0.945]	1.71s
Llama-3B + Dense	0.809	[0.759, 0.856]	0.056	[0.025, 0.094]	0.924	[0.907, 0.940]	1.64s
Llama-3B + Hybrid	0.813	[0.767, 0.858]	0.049	[0.024, 0.077]	0.930	[0.912, 0.946]	1.59s
Nemotron-4B no_mem	0.383	[0.317, 0.448]	0.189	[0.129, 0.254]	0.834	[0.800, 0.865]	1.23s
Nemotron-4B + BM25	0.388	[0.322, 0.455]	0.178	[0.120, 0.240]	0.819	[0.785, 0.851]	3.34s
Nemotron-4B + Dense	0.396	[0.328, 0.465]	0.184	[0.122, 0.251]	0.828	[0.795, 0.859]	3.63s
Nemotron-4B + Hybrid	0.356	[0.295, 0.418]	0.204	[0.138, 0.274]	0.835	[0.801, 0.866]	3.54s
Qwen-14B no_mem	0.819	[0.775, 0.863]	0.199	[0.145, 0.256]	0.944	[0.929, 0.958]	3.80s
Qwen-14B + Hybrid†	0.704	[0.630, 0.778]	0.640	[0.541, 0.721]	0.957	[0.936, 0.975]	10.51s
Llama-3B + Oracle	0.837	[0.787, 0.881]	0.046	[0.016, 0.077]	0.938	[0.922, 0.953]	1.54s
Nemotron-4B + Oracle	0.406	[0.349, 0.478]	0.209	[0.143, 0.274]	0.821	[0.784, 0.855]	1.29s



We also examined per-template variation (person, trip, project). Llama-3B showed consistent improvement across all three templates with any retrieval method, with the largest gain on the ‘project’ template (+0.14 recall with Hybrid).

Nemotron-4B showed no significant variation across templates, reinforcing that the model factor dominates over conversation type. Full per-template breakdown is available in supplementary materials.

A. Model-Dependent Memory Utility

Table II presents pairwise differences versus the no-memory baseline for both SLMs. The pattern is stark: Llama-3B benefits from all three retrieval methods on recall (+0.122 to +0.130, all significant) while Nemotron-4B benefits from none (+0.005 to +0.013, all not significant). The no-memory baselines explain why—Llama-3B already recalls 68% of facts with 6% hallucination, while Nemotron-4B recalls only 38% with 19% hallucination. This +0.300 recall gap [0.211, 0.388] means Llama-3B has a strong foundation for retrieval to build on, whereas Nemotron-4B struggles to utilize even the context it is given directly. The width of the 95% CIs (typically ± 0.06 for recall, ± 0.07 for hallucination) indicates that our sample size of 100 conversations provides adequate precision for detecting the large effects observed (e.g., +0.13 recall for Llama-3B). Smaller effects, such as the +0.005 recall for Nemotron-4B + BM25, would require approximately 400 conversations to achieve similar precision, illustrating the sample size demands of detecting subtle retrieval effects in weaker models. The Nemotron-4B result is not a failure of the retrievers but a reflection of the model’s limited capacity to benefit from external context. Nemotron-4B + Hybrid shows negative point-estimate recall (−0.027), though not significant, suggesting that hybrid retrieval may introduce noise for a less capable model—the fused context from both retrievers could be harder for a less capable model to parse than either retriever alone. Figure 3 visualizes the recall–hallucination trade-off.

Table 3 Retrieval effects vs. no-memory baseline

Model / Comparison		Delta Recall (95% CI)	Delta Halluc. (95% CI)
Llama-3B vs. no_mem	BM25	+0.122 [+0.096, +0.196]	+0.003 [−0.038, +0.046]
Llama-3B vs. no_mem	Dense	+0.126 [+0.054, +0.199]	−0.004 [−0.047, +0.038]
Llama-3B vs. no_mem	Hybrid	+0.130 [+0.055, +0.205]	−0.012 [−0.051, +0.025]
Nemotron-4B vs. no_mem	BM25	+0.005 [−0.077, +0.089]	−0.011 [−0.086, +0.063]
Nemotron-4B vs. no_mem	Dense	+0.013 [−0.071, +0.098]	−0.005 [−0.082, +0.071]
Nemotron-4B vs. no_mem	Hybrid	−0.027 [−0.108, +0.055]	+0.015 [−0.064, +0.093]

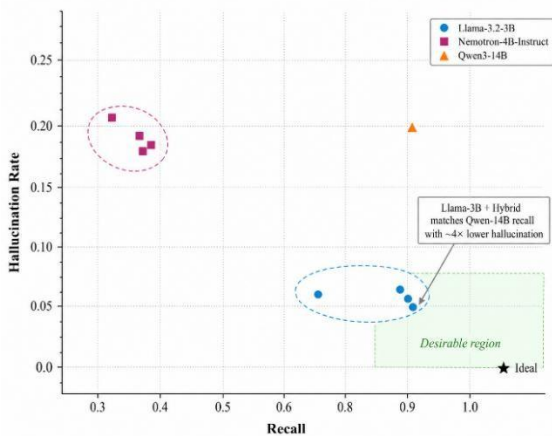


Figure 3. Recall vs. hallucination scatter. The desirable region (upper-left) is occupied exclusively by Llama-3B variants.

B. Cross-Model Comparison

Table IV compares Llama-3B + Hybrid against Qwen-14B. The two are indistinguishable on recall (0.813 vs. 0.819, not significant) and completeness (0.930 vs. 0.944, not significant). On hallucination, Llama-3B + Hybrid achieves 0.049 vs. Qwen-14B’s 0.199— $\sim 4\times$ fewer fabrications, significant. The 3B model is also $2.4\times$ faster (1.59s vs. 3.80s). This comparison is asymmetric (memory vs. no memory) and demonstrates what a capable small model can achieve with retrieval support.

Table 4 Llama-3b + Hybrid vs. Qwen-14b

Metric	Llama-3B+ Hybrid	Qwen-14B	Diff. (95% CI)	Sig.?
Recall	0.813	0.819	−0.006 [−0.065, +0.054]	No
Hallucination	0.049	0.199	−0.150 [−0.213, −0.091]	Yes
Completeness	0.930	0.944	−0.014 [−0.034, +0.006]	No
Latency	1.59s	3.80s	−2.21s	—

Symmetric comparison. With hybrid memory added to Qwen-14B, recall drops to 0.704 [0.630, 0.778] and the hallucination rate rises to 0.640 [0.541, 0.721], meaning memory augmentation actively degrades rather than helps the larger model. Llama-3B + Hybrid thus outperforms Qwen-14B + Hybrid on recall (0.813 vs. 0.704) and maintains a much lower hallucination rate (0.049 vs. 0.640). This indicates that even a larger, capable model can be disrupted by retrieval context noise in this setting.

C. Retrieval Quality and Verbosity Confound

To separate retrieval failure from generation failure, we computed retrieval recall@3 for each retriever: the fraction of recall questions for which the ground-truth answer text appears in the retrieved top-3 context. BM25 surfaces the answer in 48.9% of cases, dense in 71.1%, and hybrid in 66.2%. Dense recall@3 exceeds hybrid because RRF merges ranked lists by rank position, and BM25’s low-precision contributions occasionally push the correct answer below the top-3 cutoff; when the answer does appear in the hybrid top-3, the combination of lexical and semantic signals makes it more salient to the generator, explaining why hybrid achieves higher generation recall (0.813) than dense (0.809) despite lower retrieval recall@3. For hits (answer present in context), Nemotron-4B still fails to use it while Llama-3B succeeds, isolating the model factor: the same context that Llama-3B exploits, Nemotron-4B ignores. BM25’s 48.9% recall@3 also means the “BM25 is not harmful” finding for Llama-3B applies primarily to the half of questions where the answer is actually surfaced.

We verified that retrieved context is byte-identical across both SLMs for the same retriever and query (1,201/1,201 turns identical). Any outcome difference between Llama-3B and Nemotron-4B is therefore attributable to the generator, not to different retrieval results.

The Qwen-14B hallucination anomaly (0.199, higher than Nemotron-4B’s 0.189) is largely explained by response verbosity. Qwen-14B responses average 513 characters, compared to 234–241 for Llama-3B and 358–381 for Nemotron-4B. The numeric-fabrication proxy triggers on long responses at ~28% for both Qwen-14B and Nemotron-4B, but only ~10–12% for Llama-3B. Short responses (<200 characters) trigger the proxy at 0–2.5% across all models. The proxy is therefore sensitive to verbosity, not only to fabrication propensity. Qwen-14B’s elevated hallucination score reflects its tendency to produce longer, more elaborate responses that are more likely to contain numeric tokens absent from the conversation. This does not imply Qwen-14B is less reliable than Nemotron-4B on non-numeric fabrication; the proxy simply cannot measure that dimension.

D. Oracle Retrieval: Capability Gating vs. Floor Effect

To distinguish whether Nemotron-4B’s failure to benefit from retrieval reflects a specific inability to integrate retrieved context (capability gating) or a general inability to process multi-turn context at all (floor effect), we introduced an oracle retrieval condition: for each recall question, the exact ground-truth answer is injected directly into the prompt, bypassing the retriever entirely.

Table 5 Oracle Retrieval (Ground-Truth Injection)

Config	Recall	95% CI	Halluc.	95% CI
Llama-3B + Oracle	0.837	[0.787, 0.881]	0.046	[0.016, 0.077]
Nemotron-4B + Oracle	0.406	[0.349, 0.478]	0.209	[0.143, 0.274]

If Nemotron-4B + Oracle recall significantly exceeds Nemotron-4B no_mem, this supports the capability-gating account (the model can use context when it is perfectly relevant). If recall remains near the no-memory baseline, a floor effect is supported. See V for discussion.

Latency. Llama-3B variants cluster at 1.59–1.71s—the retrieval overhead for the 3B model is minimal. Nemotron-4B + retrieval doubles to 3.34–3.63s vs. 1.23s without, but this increase combined with no metric benefit makes memory augmentation strictly worse for Nemotron-4B. The Nemotron-4B retrieval latency increase may reflect NIM API behavior for that model rather than an intrinsic cost of retrieval; these figures should therefore be treated as indicative.

V. DISCUSSION

Model capability is associated with memory utility. The central finding is that model capability—rather than retriever choice—is associated with whether memory helps.

Llama-3B benefits from all three retrieval methods (+0.122 to +0.130 recall, all significant); Nemotron-4B shows no statistically significant benefit. The no-memory baselines explain why: Llama-3B already recalls 68% of facts with 6% hallucination, while Nemotron-4B recalls only 38% with 19% hallucination. The mechanism is not yet isolated—Llama-3.2-3B and Nemotron-4B-Instruct differ in architecture (grouped-query attention vs. standard), training data composition (multilingual emphasis vs. unknown), and instruction-tuning quality. Any of these could explain the capability gap.

The oracle retrieval results shed further light. When the exact ground-truth context is injected directly into the prompt, Llama-3B’s recall rises significantly to 0.837 [0.787, 0.881], showing it can leverage perfect context. However, Nemotron-4B’s recall remains statistically indistinguishable from its baseline (0.406 [0.349, 0.478] vs. 0.383 [0.317, 0.448]). This lack of improvement under perfect context strongly supports the floor effect hypothesis over capability gating: Nemotron-4B is fundamentally unable to process and extract facts from long multi-turn dialogue histories in this setting, even when the retrieval step is flawless.

This finding also reframes Retrieval-Induced Hallucination (RIH): in a preliminary single-model study (unpublished) we attributed RIH to the retriever, but the multi-model data show RIH is model-dependent. For Llama-3B, hallucination is flat across all retrieval methods; for Nemotron-4B, it stays at its elevated baseline. RIH occurs when a model lacks the capacity to filter irrelevant retrieved context, not as an inherent property of any retriever.

A 3B model with hybrid retrieval compares favorably to a 14B model. Llama-3B + Hybrid matches Qwen3-14B without memory on recall (0.813 vs. 0.819, not significant) while achieving lower hallucination as measured by our length-sensitive proxy (0.049 vs. 0.199, significant) and 2.4× lower latency (1.59s vs. 3.80s). When Qwen-14B is also augmented with hybrid memory, its performance degrades significantly, with recall dropping to 0.704 [0.630, 0.778] and hallucination rising to 0.640 [0.541, 0.721]. This degradation shows that a smaller, well-augmented model (Llama-3B + Hybrid, 0.813 recall) can outperform a memory-augmented larger model (Qwen-14B + Hybrid, 0.704 recall), suggesting that retrieval noise is a critical bottleneck that affects larger models differently. For hallucination-sensitive deployments where a larger model is used without memory augmentation, a well-augmented 3B model is a compelling alternative.

Practical implications. For practitioners building memory-augmented SLM systems: (1) model selection comes first—choose a model that demonstrates strong baseline context utilization (high no-memory recall, low hallucination); (2) retriever selection comes second—for capable models, all reasonable retrieval methods help, and even BM25 is not harmful when the model can filter irrelevant passages; (3) always benchmark against a no-memory baseline to verify memory actually helps for your specific model; (4) consider the full cost profile—a smaller model with memory can match a larger model on recall while producing fewer apparent fabrications, making it a compelling choice for cost-sensitive and latency-sensitive

deployments. Rough cost estimation on the NVIDIA NIM API (these figures depend on specific API pricing and may not generalize to self-hosted deployments) suggests that Llama-3B + Hybrid retrieval costs approximately 0.3× the per-token price of Qwen-14B while achieving comparable recall and 2.4× lower latency.

Validity. Our metrics are heuristic (fuzzy matching for recall, numeric-fabrication proxy for hallucination) and best read as directional indicators; claims rest on between-configuration comparisons robust to threshold choice. The data is synthetic and limited to two SLMs in Bahasa Indonesia; generalization to other models and languages is future work. Our synthetic conversations contain explicit recall questions with clear ground-truth facts. Real human conversations often involve implicit recall, topic shifts, and noisy or contradictory information. The capability-gating effect may be even more pronounced in noisier settings, or conversely, models may learn to ignore retrieval entirely if the signal-to-noise ratio is too low. Human evaluation on real chat logs is needed to validate the generalizability of our findings. The Nemotron-4B retrieval latency increase may reflect NIM API behavior. All pairwise comparisons use bootstrap CIs (20,000 resamples) with significance declared only when the 95% CI excludes zero.

VI. CONCLUSION

We set out to ask whether external memory helps a small language model recall facts in multi-turn conversation, and found that the answer depends on the model. Llama-3.2-3B benefits significantly from all three retrieval methods—BM25, dense, and hybrid—with hybrid retrieval achieving recall of 0.813 and hallucination of only 0.049. Nemotron-4B-Instruct, despite being in the same size class, benefits from no retrieval method: memory is inert for this model. The difference traces to baseline capability. Llama-3B already recalls 68% of facts without memory; Nemotron-4B recalls only 38%. Retrieval amplifies existing capability but cannot substitute for it.

The practical finding is that a 3B model with hybrid retrieval matches a 14B model on recall (0.813 vs. 0.819, not significant) while producing ~4× fewer hallucinations (0.049 vs. 0.199, significant). This inverts the usual assumption that larger models are always more reliable. For hallucination-sensitive deployments, a well-augmented small model may be preferable to a larger one.

We reframe Retrieval-Induced Hallucination as model-dependent rather than retriever-dependent. Whether retrieval helps, harms, or is inert depends on the model’s capacity to leverage retrieved context. Model selection is therefore a first-order design decision, and retriever selection is second-order. Oracle retrieval results (which show Llama-3B rising to 0.837 recall while Nemotron-4B remains flat at 0.406) provide further evidence for this framework, confirming that Nemotron-4B’s performance is limited by a fundamental context-processing floor rather than retrieval-integration capability. Future work should: (1) test this framework across more SLM families to determine how broadly the capability-gating effect holds; (2) evaluate on real-world

human dialogue beyond synthetic conversations; (3) replace heuristic metrics with human or LLM-judged evaluation for recall and hallucination; (4) investigate what architectural or training properties—such as instruction-tuning dataset composition—influence a model’s capacity to benefit from retrieved memory context.

A. Data Availability

Dataset, scripts, and code available from the authors on reasonable request.

B. AI Usage Disclosure

LLMs were used as objects of study and as tools for dataset generation and manuscript drafting. All experimental design, analysis, and final wording are the authors’ own.

C. Ethics Statement

This study uses only synthetic data with no human subjects or personal data.

D. Author Contributions, Funding, and Conflicts

The authors jointly designed the study, implemented the pipeline, ran experiments, and wrote the manuscript. No external funding. No conflicts of interest.

REFERENCES

- [1] P. Lewis *et al.*, “Retrieval-augmented generation for knowledge-intensive NLP tasks,” in *Proc. NeurIPS*, 2020. [Online]. Available: <https://arxiv.org/abs/2005.11401>
- [2] V. Karpukhin *et al.*, “Dense passage retrieval for open-domain question answering,” in *Proc. EMNLP*, 2020. [Online]. Available: <https://arxiv.org/abs/2004.04906>
- [3] S. E. Robertson and H. Zaragoza, “The probabilistic relevance framework: BM25 and beyond,” *Found. Trends Inf. Retr.*, vol. 3, no. 4, pp. 333–389, 2009.
- [4] Y. Gao *et al.*, “Retrieval-augmented generation: A comprehensive survey of architectures, enhancements, and robustness frontiers,” 2025. [Online]. Available: <https://arxiv.org/abs/2506.00054>
- [5] X. Ma *et al.*, “A replication study of dense passage retriever,” 2021. [Online]. Available: <https://arxiv.org/abs/2104.05740>
- [6] C. Sun *et al.*, “OnionEval: A unified evaluation of fact-conflicting hallucination for small-large language models,” 2025. [Online]. Available: <https://arxiv.org/abs/2501.12975>
- [7] R. Zhang *et al.*, “Knowledge Access Beats Model Size: Memory Augmented Routing for Persistent AI Agents,” 2026. [Online]. Available: <https://arxiv.org/abs/2603.23013>
- [8] W. Christian, D. Adamlu, A. Yu, and D. Suhartono, “Bridging language gaps with adaptive RAG: Improving Indonesian language question answering,” 2025. [Online]. Available: <https://arxiv.org/abs/2510.21068>
- [9] S. Chakraborty *et al.*, “mtRAG: A multi-turn conversational benchmark for evaluating retrieval-augmented generation systems,” *Trans. Assoc. Comput. Linguist.*, 2025. [Online]. Available: <https://arxiv.org/abs/2501.13885>
- [10] Y. Zhao *et al.*, “When retrieval succeeds and fails: Rethinking retrieval-augmented generation for LLMs,” 2025. [Online]. Available: <https://arxiv.org/abs/2510.09106>
- [11] N. Liu *et al.*, “Quantifying the distracting effect of retrieved passages in RAG,” 2025. [Online]. Available: <https://arxiv.org/abs/2505.06914>
- [12] N. Reimers and I. Gurevych, “Sentence-BERT: Sentence embeddings using Siamese BERT-networks,” in *Proc. EMNLP*, 2019. [Online]. Available: <https://arxiv.org/abs/1908.10084>

- [13] G. V. Cormack, C. L. A. Clarke, and S. Buettcher, “Reciprocal rank fusion outperforms Condorcet and individual rank learning methods,” in *Proc. SIGIR*, 2009.
- [14] H. Touvron *et al.*, “LLaMA: Open and efficient foundation language models,” 2023. [Online]. Available: <https://arxiv.org/abs/2302.13971>
- [15] B. Wilie *et al.*, “IndoNLU: Benchmark and resources for evaluating Indonesian natural language understanding,” in *Proc. AACL*, 2020. [Online]. Available: <https://arxiv.org/abs/2009.05387>
- [16] M. McKee, “SelRoute: Query-Type-Aware Routing for Long-Term Conversational Memory Retrieval,” 2026. [Online]. Available: <https://arxiv.org/abs/2604.02431>
- [17] C. Packer *et al.*, “MemGPT: Towards LLMs as operating systems,” 2023. [Online]. Available: <https://arxiv.org/abs/2310.08560>
- [18] A. Yang *et al.*, “Qwen technical report,” 2024. [Online]. Available: <https://arxiv.org/abs/2412.15115>
- [19] A. Dubey *et al.*, “The Llama 3 herd of models,” 2024. [Online]. Available: <https://arxiv.org/abs/2407.21783> N. F. Liu *et al.*, “Lost in the middle: How language models use long contexts,” 2024. [Online]. Available: <https://arxiv.org/abs/2307.03172>
- [20] G. Izacard *et al.*, “Unsupervised dense information retrieval with contrastive learning,” 2022. [Online]. Available: <https://arxiv.org/abs/2112.09118>
- [21] X. Zhang *et al.*, “MIRACL: A multilingual information retrieval across a continuum of languages,” 2022. [Online]. Available: <https://arxiv.org/abs/2210.09984>

Advancing Quantum Technology Workforce: Logistics Industry Insights into Qualification and Training Needs

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ABSTRACT — The logistics sector is undergoing a shift toward digitalization and new quantum-related technologies which are changing structures of operations, the expectations of employees and the competencies needed. Although there has been a rise in advanced technological integration in logistics operations, there is limited discussion on how organizations perceive the qualification requirements and training needs for developing a quantum-ready logistics workforce. The current study therefore sheds light on the question of what are the necessary skills, competence and training needs for quantum enabled logistics environments that logistics organizations are identifying as essential. The design used was qualitative research which utilized semi-structured interviews with 16 logistics managers from different logistics and supply chain organizations in Malaysia. Thematic analysis with the aid of NVivo software was used to analyze the data collected. The results indicated six dominant themes: Interdisciplinary competency shift towards digital and quantum adjacent, Qualification misalignment between industry needs and workforce capabilities, Organizational digital maturity and readiness for adaptation towards quantum, Training system limitations and fragmented workforce development pathways, Resistance towards digital transformation and barriers to workforce adaptation, and Ecosystem and stakeholder collaboration for sustainable quantum workforce development. Results prove that digital adaptability, analytical ability, systems thinking, and constant technological learning, are now more important than just operational skills to prepare the logistics workforce. The study provides theoretically and practically relevant as it gives insights to the development of an organization's human capital for future technologically advanced logistics ecosystems.

KEYWORDS: Quantum-ready workforce, logistics industry, digital transformation, workforce development, digital competencies, quantum technology integration.

I. INTRODUCTION

Quantum technologies are transforming industrial processes, digital infrastructure, and computational power in a variety of industries, including logistics and supply chain management. In recent years, quantum computing, quantum sensing, and quantum communication have been seen as promising solutions to highly complex optimization problems in routing, scheduling, warehouse operations, demand forecasting, and real-time decision-making in

logistics systems [1]. The introduction of new technologies, such as quantum technologies, is likely to further increase the demand for a highly skilled workforce able to operate in a digitally advanced environment, as logistics operators continue their shift towards Industry 4.0 and data-driven ecosystems. Even though investments are made in technology, many logistics organizations are not well-equipped with workforce and digital skills, or with structured training systems, to facilitate the quantum transformation.

Recent research shows that it is very difficult for industries using cutting-edge technologies to recruit and retain employees with interdisciplinary digital competencies, such as data analysis, artificial intelligence, automation, and computational skills [2, 3]. In the logistics and transportation industry, the digital transformation has driven the growing need for staff with multi-disciplinary skills in technical knowledge, systems thinking, operational management, and digital agility. Meanwhile, organizations are facing a lack of skilled staff to drive technologically demanding processes. This challenge is even more important when quantum technologies are introduced, as the skills required for quantum systems differ from those taught in traditional logistics training programs. Existing logistics education and workforce development programs continue to be dominated by traditional operational skills and lack coverage of quantum readiness, advanced computational literacy, or interdisciplinary digital skills.

However, there is still a lack of empirical knowledge about the specific requirements of logistics organizations regarding the competencies their quantum technology workforce needs, the types of qualifications perceived as critical, and how to structure training ecosystems to enable digital transformation in logistics organizations [4]. This indicates a major research gap in preparing logistics organizations for quantum-based operations is still in its early stages and lacks clarity on a possible approach to workforce readiness. Additionally, the contribution of organizational digitalization and stakeholder cooperation to the development of workforce strategies for quantum technologies has received little attention. Increasingly, stakeholders such as universities, government, logistics associations, technology suppliers, and industrial training institutions are playing a crucial role in ensuring the

transition of the workforce into technologically advanced logistics ecosystems.

Another aspect that is not dealt with is the difference between the level of technological development and the workers' lack of skill development. While many organizations are investing significant resources in their digital infrastructure, automation, and intelligent logistics systems, they are not allocating the same resources to upskilling and training their staff in sustainability. This leads to organizational vulnerability, where employee readiness is lagging behind digital transformation [5]. In a logistics context where complexity, timeliness, and interconnected supply chains are paramount, lacking quantum-ready skills could be a major obstacle to adopting new technology and achieving competitiveness. This study, therefore, focuses on the logistics industry's awareness of the need to qualify and train for quantum technology and on the role of stakeholders in workforce development in relation to organizational digitalization requirements. Specifically, this study aims to understand the requirements that logistics organizations consider essential to provide a quantum-ready workforce that can adapt to logistics operations enabled by quantum technologies.

Thus the study aim is to explore how logistics organisations perceive the qualification requirements needed to support quantum technology integration examines what training needs and digital competencies are considered essential for developing a quantum-ready logistics workforce. The novelty of this study is in the integration of the quantum technology workforce development and logistics digitalization, as well as the perspectives of all the stakeholders concerned. This helps to gain a more comprehensive view of the preparedness of the workforce, not only in terms of the technical skills acquired during training, but also in a broader sense, and can help develop ideas for future-oriented logistics talent strategies.

II. UNDERPINNING THEORY

This study uses the Sociotechnical Systems Theory (STS) and Actor-Network Theory (ANT) to gain insight into the perception of qualifications and training requirements for the organization of logistics to foster a quantum-ready workforce in a digitally transformed logistics organization. The two lenses are merged to capture the internal dynamics of the organization and the broader technological-institutional interactions that influence the evolving development of workers in emerging logistical settings.

According to [6], organizational performance is an emerging process that is influenced by the dynamic between social systems (people, skills, culture, and structure) and technical systems (technology, tools, and processes). While technology adoption is a single factor for change, STS requires the optimization of human capabilities together with technological systems [7]. STS is relevant for this research, because it can give insight into the perception of qualification requirements in the field of integration of quantum technologies in logistics organizations. Logistics operations are increasingly digitalized, and organizations not only invest in the technology to become more capable but they know they must invest in people's capabilities in tandem. The STS principle that socio-technical balance is essential for sustainable performance has been echoed in recent studies, which indicated that digital transformation in the logistics

sector is likely to fail if the socio-technical elements and technological development are out of balance [7].

In addition, this study proposes using ANT to better understand the role of organizational decision-making, as well as the wider technological infrastructures and institutional arrangements in shaping training needs and digital competencies [8, 9]. This aligns with ANT's notion that technology is not "just there" but a change agent in relation to organizational practices [10]. For workforce development in preparation for quantum readiness, ANT aids in the understanding of the interdependencies and the impact of emerging technologies, educational institutions, policy and logistics companies on competency development. For example, not only do training platforms and digital systems support learning, but their design and use create the skills that are needed, and how workers work with them. Therefore, the combination STS and ANT mutually complement each other and offers a more comprehensive understanding of the quantum workforce development as an organizational change and a networked socio-technical phenomenon.

III. METHODOLOGY

A qualitative research design was used to gain insights into logistics managers' experiences with the qualifications needed to equip employees for quantum technology and the training needs in a digitally transforming logistics environment. The selected method enables a detailed understanding of the relationship between the organizational experience, digitalization processes and the development and learning of the working population in accordance with real conditions of implementation. The qualitative design would be more appropriate in the context of new technologies, such as quantum logistics, where empirical knowledge remains limited and an understanding of the technology through an interpretive lens is required [11].

A total of 16 logistics managers from various subsectors, including transportation, warehousing, freight forwarding, supply chain coordination, and digital logistics operations, were included in the study. To ensure participants had the necessary managerial experience in workforce development, digital transformation, and operational decision-making, purposive sampling was used. The method is applicable when information-rich cases are desired that can directly relate to the research objectives [12]. In addition, a snowball sampling approach was used, as the leadership positions in logistics digitalization are highly specialized and not readily accessible to researchers in some organizations.

In line with the qualitative sampling guidance, a sample size of 16 was deemed acceptable, as it would provide enough data for thematic saturation and in-depth explorations of perspectives [13]. The study used semi-structured interviews over 5 months (January-May 2026) to gather data. The approach was chosen because it enables participants to share experiences in depth while maintaining consistency with the main subject areas of the discussion, including workforce skills, digital skills, training systems, and stakeholder collaboration. Semi-structured interviews are well-suited for investigating new technological contexts in which the participants might have varying interpretations and experiences [14]. Interviews were conducted one-on-one for about 45–60 minutes. This method was chosen because logistics management jobs are operational in nature, and participants may not have enough time for online sessions.

The face-to-face interaction also helped build rapport and deepen the discussion of organizational issues related to digital transformation and workforce preparation. All interviews were audio-recorded with the participant's consent and transcribed verbatim to ensure accurate, complete data capture.

Qualitative data were analyzed and interpreted using thematic analysis, which involved identifying, analyzing, and interpreting patterns across the data. It is a flexible, systematic approach often adopted for studying phenomena within an organization and the workforce [14]. The analysis was carried out in six phases: familiarization with data, initial coding, theme development, theme review, theme definition, and the final report. Themes were developed, data were organized, and coding was systematic using NVivo software. NVivo provided a structured way to categorize interview transcripts and facilitated the easy retrieval of coded segments, thereby bringing transparency and rigor to the study.

Several approaches to trustworthiness were employed in order to achieve methodological rigor. To ensure measures credibility, a lengthy process of exposure to the data and participant's validation was conducted [15]. For reliability, a well-documented audit trail was maintained, which included all the stages of data collection and analysis [16]. Further, reflexivity was employed to validate the results of the study, as it helps in reducing researcher bias and helps to ensure that the results of the study are grounded in the narratives of the participants [17]. The comprehensive description of participants, organisational context and industry setting allowed readers to assess the transferability of the findings to their own logistics setting by analysing the applicability of the findings to their own [18].

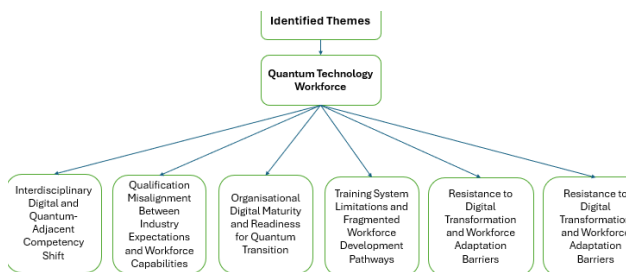


Figure 1. Identified Themes of the Study.

Theme 1: Interdisciplinary Digital and Quantum-Adjacent Competency Shift.

The first theme is that logistics organizations are seeking a more interdisciplinary, digital competency among their employees, in addition to logistics skills. The logistics sector is becoming more technologically oriented and the workforce is required to know how to operate systems, analyze data and use automated decision-making tools rather than merely experience

P1 explained:

"Logistics operations today are highly dependent on digital systems, so employees must understand technology and data, not only transportation procedures."

Similarly, P2 described the changing nature of logistics work, stating:

"We are no longer looking for workers who only follow manual instructions because the industry now depends on integrated digital systems."

The narratives demonstrate that logistics companies are increasingly connecting future employees' ability with analytical thinking and digital adaptability.

It was also noted that in the future, quantum-related technologies and advanced computational systems will likely be part of the expectations for today's workforce. P3 shared: allowed readers to assess the transferability of the findings to their own logistics setting by analysing the applicability of the findings to their own [18].

IV. FINDINGS

The analysis yielded six major themes: Interdisciplinary competency shift towards digital and quantum adjacent, Qualification misalignment between industry needs and workforce capabilities, Organizational digital maturity and readiness for adaptation towards quantum, Training system limitations and fragmented workforce development pathways, Resistance towards digital transformation and barriers to workforce adaptation, and Ecosystem and stakeholder collaboration for sustainable quantum workforce development. The themes found were inductive, constructed repeatedly and continuously across the participant stories, coding, and theoretical interpretation, supported by the theories of STS and ANT. Six themes of the study were identified (shown in Figure 1) and will be discussed in detail

"In the future, logistics employees may need to understand how advanced optimisation systems work because decision-making is becoming more automated."

Likewise, P4 explained:

"The workforce must become more flexible because logistics technology changes very quickly and employees cannot depend only on traditional experience anymore."

The findings therefore indicate that workforce qualifications are evolving toward hybrid competencies combining logistics knowledge with digital fluency, systems thinking, and adaptive learning capability.

Theme 2: Qualification Misalignment Between Industry Expectations and Workforce Capabilities

The second theme focuses on the persistent lack of skills among the current workforce and the needs of industry. A high number of participants have reported that the digital competencies of many employees and graduates were not qualified enough for increasingly digitalized logistics business.

P5 explained:

"Many new employees understand logistics theory, but they struggle when handling real digital systems used in daily operations."

Similarly, P6 described challenges associated with analytical capability gaps, stating:

"Some workers are comfortable with manual processes, but they cannot interpret digital reports or operational analytics properly."

The response indicates that workforce development is not keeping up with technology changes in logistics companies.

The participants also said that education is still mostly focused and not well aligned with future technological needs.

P7 shared:

"Graduates entering logistics usually have basic operational knowledge, but they are not prepared for advanced digital platforms or automated systems."

Likewise, P8 explained:

"The industry expects workers to adapt quickly to technology, but many employees have never been exposed to these systems before joining."

The findings reveal a significant gap between organizational needs and employee readiness, particularly in digital literacy, analytical thinking, and technology adaptation.

Theme 3: Organisational Digital Maturity and Readiness for Quantum Transition

The third theme shows that logistics organisations are in various stages of maturity and preparedness to take logistics technology transformation to the next stage. Organizational digitalization was seen consistently as not complete, and not as an uniform process across operational systems and departments.

P9 explained:

"Our company already uses automation and digital tracking systems, but not every department is equally prepared to use them effectively."

Similarly, P10 stated:

"Technology implementation is happening very fast, but workforce readiness inside the organisation is still developing slowly."

Participants also highlighted the importance of leadership commitment and organisational culture in supporting digital transformation. P11 shared:

"When management actively supports digitalisation, employees become more willing to learn and adapt to the systems."

However, several participants acknowledged that organisations continue to face operational and infrastructural limitations. P12 explained:

"Some organisations invest in technology, but they do not invest equally in preparing employees to understand and use the systems properly."

In addition to technological investments, the results indicate that readiness to future logistics transformation using quantum technologies is also influenced by maturity in digital integration, leadership support and capability development of the workforce.

Theme 4: Training System Limitations and Fragmented Workforce Development Pathways

The fourth theme centers on current challenges to training systems and structures for workforce development. On this subject, all participants confirmed that logistics training programs are outdated, not modern, poorly structured and do not match the digital technology today.

P13 explained:

"Most logistics training programmes still focus on traditional operational skills and do not prepare workers for future digital transformation requirements."

Similarly, P14 stated:

"Training is usually conducted only when new systems are introduced, not as continuous workforce development."

Participants also highlighted weak collaboration between educational institutions and logistics organisations. P15 shared:

"There is still a gap between what universities teach and what logistics companies actually require in real operations."

Likewise, P16 explained:

"Employees often need to learn digital systems independently because structured long-term training pathways are still very limited."

These results indicate that there are few proactive pathways for workforce development and for the long-term development of the ability to respond to future quantum technology-enabled logistics environments.

Theme 5: Resistance to Digital Transformation and Workforce Adaptation Barriers

The fifth theme is on human-centred aspects of workforce adaptation and digital transformation. The major obstacles identified to being workforce ready were lack of digital confidence, technical complexity, and employee resistance.

P1 reflected:

"Some employees avoid using new systems because they are afraid of making mistakes or slowing down operations."

Similarly, P3 explained:

"Older workers especially find it difficult to adapt because they are more comfortable with traditional working methods."

Participants also described how operational pressure intensified adaptation difficulties. P5 shared:

"Employees are expected to learn new systems quickly while still maintaining operational performance and meeting delivery deadlines."

Likewise, P7 admitted:

"When new digital systems were introduced, many workers felt stressed because they received very little guidance or support."

The narratives show that the psychological and behavioural changes required for digital transformation are as critical as the technology and will need continual support and learning.

Theme 6: Ecosystem and Stakeholder Collaboration for Sustainable Quantum Workforce Development

The sixth theme focuses on the importance of establishing ecosystem partnerships between logistics companies, universities, government and technology companies to support a sustainable transition for the workforce.

P10 explained:

"No single organisation can prepare workers for future logistics technologies alone because the skill requirements are becoming too complex."

Similarly, P12 stated:

"Universities, government agencies, and logistics companies need stronger collaboration to ensure training matches future industry requirements."

Participants also highlighted the importance of policy support and industry-driven training initiatives. P14 shared:

"Government support is important because many organisations cannot afford continuous advanced digital training independently."

Likewise, P16 explained:

"Technology providers should work more closely with logistics companies because they understand how future systems and platforms will evolve."

The findings reveal that workforce readiness cannot be accomplished by individual organizations, but rather by a collaborative effort among stakeholders. The results also signal a need for a coordinated effort and a thinking mindset that looks at the whole system in the future to educate the quantum workforce and to connect the policy, infrastructure and technological capacities for a long-term logistics transformation.

V. DISCUSSION

This study examines the perception of logistics organizations about the requirements for and training needs of building a quantum-ready workforce within a digitally transformed logistics organization. The results were summarized in six themes which together answered the two research questions and showed that technological innovation, readiness of organizations, adaptability of the workforce and collaboration with stakeholders all influence the process of workforce change within the logistics sector.

Theme 1: Interdisciplinary Digital and Quantum-Adjacent Competency Shift

The results showed that the skills of logistics organizations are increasingly oriented toward interdisciplinary skills in digital and quantum-adjacent domains. The participants repeatedly stressed that logistics workers today must be digitally literate, able to analyze situations, think systemically, and adapt to technologies. This underscores the shift in logistics environments towards data- and technology-driven systems that involve interactions between employees and automated platforms, digital tracking systems, and smart operational workflows. The results support the latest research indicating that the Industry 4.0 transformation has shifted expectations for workforce competency toward greater reliance on hybrid technical and cognitive skills [19, 20]. Other scholars argued that the discussion of competencies related to quantum is still premature, as applications of quantum in logistics are still emerging [21, 22]. However, this was not enough to reduce the participants' sense of the importance of anticipatory workforce development in light of the uncertainty of future technological disruption. As a result, workers' skills are being viewed as interdisciplinary and future-oriented rather than more operationally focused.

Theme 2: Qualification Misalignment Between Industry Expectations and Workforce Capabilities

The results also showed a significant gap between the qualifications of the existing workforce and the organization's expectations. Participants reported that, in many cases, there is a mismatch between theoretical knowledge and practical digital competency, analytical skills, and technological adaptability among employees and graduates in the increasingly digitalized logistics sector. Organizations were identified as moving ahead more quickly than workforce preparation systems. This study confirms the recent literature, which claims that logistics education and qualification systems still have a strong operational focus despite the digital transformation of supply chain industries [23, 24]. However, other scholars argue that competency gaps can be competently addressed over time, with minimal redesign of qualifications, as a result of employers' exposure to them in their workplaces [25, 26]. The results of this study, however, contradict this, showing that passive exposure is insufficient to control complex digital systems. The participants discussed dependence on informal learning processes, such as peer and self-learning, which have been insufficiently structured. Thus, the results indicate a need for a significant overhaul of workforce qualification systems, incorporating digital literacy, analytical thinking, and adaptive technological skills.

Theme 3: Organisational Digital Maturity and Readiness for Quantum Transition

The findings also showed that organizational digital maturity has a significant impact on employee readiness for subsequent technological transformation. Organizations' readiness was also different, with some companies showing a high degree of digital integration and others maintaining disjointed manual operations. Importantly, participants highlighted that technological investments alone are not enough if workforce capability development, leadership support, and adaptability of the organization are not ensured. The results are consistent with recent digital transformation research, which posits that aligning technical and human resources is crucial to the success of introducing technology [27]. The results also align with the STS that focuses on interaction between technological systems and social systems in balance. Others, however, contend that even if there is still a lack of readiness, advanced automation can achieve operational efficiency on its own [28, 29]. This article's results contradict that view and point out that lack of workforce readiness can result in underutilisation of digital systems, inefficiencies in operations, and employee uncertainty. Thus, organizations need to be technologically mature and continually develop their staff skills for future logistics transformation to become a viable reality.

Theme 4: Training System Limitations and Fragmented Workforce Development Pathways

The research found key gaps in the logistics training systems and pathways. The training programs were generally perceived as poorly coordinated, not proactive towards the changing technological needs and insufficient. There were often problems with employees adapting systems following training. The training was often not conducted until systems were in place, resulting in challenges for staff with adaptation. The findings align with recent research showing that most of the logistics workforce development systems continue to be less agile in preparing for the transformation

of logistics [30]. The existing literature also suggests that there is a need for learning ecosystems over a single technology training program [31]. But there is also the possibility that organizations might hesitate to invest in long-term training due to the uncertainty of technological changes and financial returns [32, 33]. The data, however, suggest that such a claim is untrue as broken training systems widen capacity gaps and adaptation challenges among the workforce. Often, employees had to learn on their own and get informal advice from colleagues, as there was little structured support, participants repeatedly explained. Therefore, it is necessary to develop integrated and continuous training systems for future technological readiness and adaptation to digitalization.

Theme 5: Resistance to Digital Transformation and Workforce Adaptation Barriers

The findings revealed that barriers to workforce adaptation significantly affect the acquisition of quantum-ready digital competencies. Technological anxiety, low confidence, resistance to change, and generational competency differences were all reported as significant barriers to digital transformation processes. Some workers who are less familiar with information technology found it difficult and complicated to work with. Technology systems appeared difficult and mentally challenging to workers who were not so familiar with technology. Such findings align with recent research indicating that digital transformation is more about behavioral and psychological change than technological change [34]. There are, however, some scholars who believe that resistance can naturally reduce over time and in the context of operation [35, 36]. The results of this research contradict this view and show that adaptation is not a natural process but rather one that requires strong organizational support, a convenient learning opportunity, and regular guidance. This was repeatedly reported as a key deficiency of the learning support that led to high levels of stress and extended resistance behaviors. Based on the results, it can be concluded that a quantum-ready logistics workforce must be technically trained and supported psychologically and behaviorally through mechanisms that enhance workers' confidence and flexibility.

Theme 6: Ecosystem and Stakeholder Collaboration for Sustainable Quantum Workforce Development

The final theme highlighted the need for collaboration among the quantum workforce ecosystem partners, including logistics organizations, educational institutions, government bodies, and technology providers, to build a sustainable quantum workforce. One constant theme was the lack of expertise and resources in any one organisation to be able to train workers for the future technologically sophisticated logistics environment. Rather, "coordinated collaboration" was seen as necessary to match the skills of the workforce with the fast-changing technology needs. The findings are also consistent with recent research indicating that workforce transformation is more dependent on the interconnectedness of innovation ecosystems involving industry collaboration, modernisation of education, and policy support [28, 37]. But other researchers warn of the problems of coordination inefficiency and governance complexity that can arise from multi-stakeholder partnerships [38, 39]. Despite these concerns, the findings illustrate that a fractured approach to logistics workforce development is not adequate to meet future demands for logistics transformation. This creates a

structural requirement for ecosystem collaboration in the context of sustainable quantum workforce capability development in evolving logistics industries in a digital era.

VI. IMPLICATIONS OF THE STUDY

A. Theoretical Implications

This research makes a theoretical contribution by advancing understanding of workforce development in digitally transforming logistics environments through a combination of socio-technical and ecosystem perspectives. Specifically, it strengthens and deepens STS by showing that the training and development of the workforce is not just a matter of balancing the social and technical subsystems, but an ongoing process influenced by emerging technologies such as AI, automation, and quantum systems. The results reveal that qualification requirements and training needs evolve in an interactive and dynamic process between technological evolution and human capability adaptation, rather than being defined as inputs into organizational structures. In addition, the study expands ANT by providing examples of how workforce development becomes a complex process involving not only human actors (managers, employees, policy makers) but also non-human actors (digital platforms, training processes, smart logistics technologies). The actors have an active influence on competency expectations, learning processes, and the organization's readiness. This helps to reinforce the theories recently proposed that technology, rather than just a tool, should be considered a part of organizational change [40]. The study challenges linear models of workforce development, arguing that the process of readiness to quantum is not linear but iterative and adaptive, shaped by organizational maturity and ecosystem collaboration. It highlights the importance of competency formation as a continuous redefinition process, driven by technological disruptions and interactions with institutions. The study provides a more comprehensive conceptual framework for quantum workforce development by establishing the socio-technical alignment and integrating it with the dynamics of network-based ecosystems in the context of logistics transformation.

B. Policymaker Implications

The findings highlight the need for Malaysia to strengthen its logistics workforce policies by integrating existing national training initiatives with emerging digital and quantum-related technologies. Current national strategies, including the National TVET Policy 2030, emphasize industry-aligned training, digital competency development, and stronger industry-academia collaboration to build a future-ready workforce. The government's allocation of RM6.8 billion for TVET and skills development in the 2024 national budget further demonstrates its commitment to large-scale upskilling and reskilling initiatives, particularly through HRD Corp programs. Additionally, frameworks such as the HRD Corp Industrial Skills Framework (IndSF) and logistics-focused initiatives like the PATH program provide structured mechanisms for competency development within the logistics sector.

Despite these efforts, existing policies remain largely centered on Industry 4.0 readiness and general digital transformation, with limited attention given to emerging technologies such as quantum computing and their implications for logistics workforce planning. This creates a

policy gap in preparing workers for future logistics systems requiring advanced digital and analytical competencies. The findings suggest that policymakers should enhance current TVET and HRD Corp initiatives by incorporating training in advanced digital systems, interdisciplinary analytics, and quantum-related logistics competencies. Furthermore, effective workforce development requires collaboration among government agencies, logistics organizations, educational institutions, and technology providers to ensure training remains aligned with technological advancements. Finally, long-term and adaptive workforce development strategies are needed to complement short-term reskilling efforts and ensure Malaysia's logistics workforce remains competitive in an increasingly digital and technologically advanced environment [41].

C. Managerial Implications

The findings highlight the importance of a multi-stakeholder logistics ecosystem in developing a quantum-ready workforce for the future logistics industry. Logistics organizations, government agencies, training institutions, and technology providers play interconnected roles within the broader socio-technical transformation environment. Logistics organizations must recognize the evolving competency requirements brought by digitalization and emerging quantum-related technologies, including data-driven decision-making, systems integration, and automated logistics management. However, organizations alone may struggle to develop these capabilities sustainably without external support. Government agencies play an important role in aligning national digitalization policies, funding workforce development initiatives, and establishing competency standards that support future logistics transformation. At the same time, training institutions need to redesign curricula and certification programs to emphasize advanced digital literacy, analytics, and basic quantum-related competencies rather than traditional operational skills alone. Technology providers contribute by facilitating knowledge transfer, providing systems training, and exposing employees to evolving logistics technologies. The study further shows that workforce competency requirements are dynamic and continuously reshaped by technological advancement and organizational digital maturity. Poor coordination among stakeholders can widen skill gaps, slow workforce adaptation, and reduce organizational readiness for advanced logistics systems. In contrast, collaborative initiatives such as industry-academia partnerships, joint training frameworks, and policy-driven competency standards improve workforce adaptability and strengthen alignment between technological innovation and human capability development. Ultimately, sustainable workforce readiness in quantum-enabled logistics depends on continuous skill development supported by effective stakeholder governance within a dynamic socio-technical ecosystem [42].

VII. LIMITATIONS OF THE STUDY AND DIRECTIONS FOR FUTURE RESEARCH

This study offers valuable insights into logistics organizations' views on qualification and training requirements for developing a quantum-ready workforce in digitally transformed logistics. However, there are several drawbacks to note. The study first targeted logistics organizations in Malaysia, as it is the country where the

context of organizational digital maturity, technological infrastructure, and skills may differ from those in other countries and industries. Hence, the results could reflect context-specific issues in Malaysia's logistics industry workforce development. Secondly, while the study explored perceptions on quantum workforce readiness, the use of quantum technologies in logistics operations is limited at the industrial level. Consequently, participants' experiences were influenced more by organizational expectations in their anticipation than by any direct, large-scale operational exposure to the new technology. This meant that the participants' perspectives were more influenced by organizational expectations in their anticipation than by any direct, large-scale operational exposure to the new technology. Third, the study focused on managerial and organizational views on workforce capability development and thus might not reflect the experiences of technical employees, technology developers, policymakers, or educational institutions engaged in future workforce capability development processes. Further, the pace of change in digital and quantum technologies could continue to shift competency needs for the workforce, organizational capacity, and training over time.

Future studies should thus broaden the scope of the investigation further and include other areas of logistics, including maritime logistics, warehouse logistics automation, aviation logistics, and cross-border supply chain logistics. Multiple countries or regional logistics ecosystems could also be included in comparative studies to gain a broader understanding of the roles that national digital policy, industrial readiness, and the educational system play in preparing the quantum workforce. In addition, this study should be followed up with research on the views of universities, technical institutions, technology providers, and policy-makers to deepen understanding of collaborative workforce development ecosystems that support future logistics transformation.

VIII. CONCLUSION

This study offers a thorough knowledge of the reconfigured human resource expectations, training agenda and capability development strategy in logistics organizations in response to the fast-paced digital transformation and quantum technology-related industry foresights. The findings indicate that logistics-related skills are not only operational-related skills anymore, but rather are becoming more and more interdisciplinary, relating to digital skills, learning skills, and skills in making decisions based on systems. An interesting aspect of the study is the shift in organisations' perception of readiness in terms of qualification, shifting towards digital ecosystems, whilst logistics became more of a secondary concern.

One of the virtues of this work and its novelty is that it highlights the logistics workforce and takes a stake in the quantum readiness discourse that is not so well-represented in the existing literature. The research adds to the knowledge base by demonstrating that organizations are already engaged in some sort of anticipatory capability development either with or without full-fledged quantum logistics systems. It also highlights that transformations in the workforce go beyond technology; they are about the combined efforts of a range of stakeholders in the ecosystem, such as industry, education, and policy, as well as effective training systems

and organizational digital maturity. To sum up, it has been found that a balanced approach of human capacity development and technological innovations is key to successful logistics transformation. An ad hoc and non-coordinated approach to stakeholder involvement could create capability gaps and inefficiencies within the organization due to digitalization [43]. The findings, therefore, emphasize the need to build human resources that are flexible, technologically capable, and future-proof, not just by acquiring technology, but also by the organization's ability to do so in a dynamic socio-technical environment.

REFERENCES

- [1] Shamsuddoha, M., Kashem, M. A., Nasir, T., Hossain, A. I., & Ahmed, M. F. (2025). Quantum Computing Applications in Supply Chain Information and Optimization: Future Scenarios and Opportunities. *Information*, 16(8), 693.
- [2] Bukartaite, R., & Hooper, D. (2023). Automation, artificial intelligence and future skills needs: an Irish perspective. *European Journal of Training and Development*, 47(10), 163-185.
- [3] Morandini, S., Fraboni, F., De Angelis, M., Puzzo, G., Giusino, D., & Pietrantonio, L. (2023). The impact of artificial intelligence on workers' skills: Upskilling and reskilling in organisations. *Informing Science*, 26, 39-68.
- [4] Marchant, G., Bazzi, R., Bowman, D., Connor, J., Davis III, R. A., Kang, E., ... & Wastek, S. (2024). Learning from emerging technology governance for guiding quantum technology. *Rich. J. L. & Tech.*, 31, 266.
- [5] Parry, E., & Battista, V. (2023). The impact of emerging technologies on work: a review of the evidence and implications for the human resource function. *Emerald Open Research*, 1(4).
- [6] Zhang, P., Dillard, N., & Cavallo, T. (2025). Navigating the limitations of algorithmic management: an integrative framework of sociotechnical systems theory (STS) and strategic HRD. *Human Resource Development Review*, 24(3), 279-303.
- [7] Thomas, A. (2024). Digitally transforming the organization through knowledge management: a socio-technical system (STS) perspective. *European Journal of Innovation Management*, 27(9), 437-460.
- [8] Aysan, H. (2026). Artificial Intelligence as a Distributed Actor: Rethinking Organizational Theory Through Sociotechnical Networks. *Artificial Intelligence and Applications*, 4(1), 92-100.
- [9] Hald, K. S., & Spring, M. (2023). Actor-network theory: a novel approach to supply chain management theory development. *Journal of Supply Chain Management*, 59(2), 87-105.
- [10] Jones, J. (2025). AI-Driven Logistics: Understanding the Transformational Impact on Global Supply Chain Networks.
- [11] Coccia, M., & Roshani, S. (2024). Evolutionary phases in emerging quantum technologies: General theoretical and managerial implications for driving technological evolution. *IEEE Transactions on Engineering Management*, 71, 8323-8338.
- [12] Nyimbili, F., & Nyimbili, L. (2024). Types of purposive sampling techniques with their examples and application in qualitative research studies.
- [13] Ahmed, S. K. (2025). Sample size for saturation in qualitative research: Debates, definitions, and strategies. *Journal of Medicine, Surgery, and Public Health*, 5, 100171.
- [14] Braun, V., & Clarke, V. (2022). Conceptual and design thinking for thematic analysis. *Qualitative Psychology*, 9(1), 3-26.
- [15] Dado, M., Spence, J. R., & Elliot, J. (2023). The case of contradictions: how prolonged engagement, reflexive journaling, and observations can contradict qualitative methods. *International Journal of Qualitative Methods*, 22, 1-12.
- [16] Almusaed, A., Almssad, A., & Yitmen, I. (2025). Qualitative data collection and management. In *Practice of Research Methodology in Civil Engineering and Architecture: A Comprehensive Guide* (pp. 417-454). Cham: Springer Nature Switzerland.
- [17] Janis, I. (2022). Strategies for establishing dependability between two qualitative intrinsic case studies: a reflexive thematic analysis. *Field Methods*, 34(3), 240-255.
- [18] Stalmeijer, R. E., Brown, M. E., & O'Brien, B. C. (2024). How to discuss transferability of qualitative research in health professions education. *The Clinical Teacher*, 21(6), e13762.
- [19] Marlapudi, K., & Lenka, U. (2024). Unlocking the potential: redefining talent and competency mapping for Industry 4.0. *Management Research Review*, 47(11), 1805-1832.
- [20] Bondin, A., & Zammit, J. P. (2025). Education 4.0 for industry 4.0: A mixed reality framework for workforce readiness in manufacturing. *Multimodal Technologies and Interaction*, 9(5), 43.
- [21] Greinert, F., Ubben, M. S., Dogan, I. N., Hilfert-Rüppell, D., & Müller, R. (2024). Advancing quantum technology workforce: industry insights into qualification and training needs. *EPJ Quantum Technology*, 11(1), 82.
- [22] Cuomo, M. T., & Foroudi, P. (2025). Tools and Techniques for Quantum Business. In *Quantum Level Business Model: A New Managerial Perspective* (pp. 83-104). Cham: Springer Nature Switzerland.
- [23] Merkert, R., Hoberg, K., & Mahadevan, K. (2023). Logistics and Supply Chain Superpowers and Skills for Survival in the "New Normal" Globalized World. *Transportation Journal*, 62(4), 369-396.
- [24] HONGSAKUL, B., LALAENG, C., & INGARD, A. (2025). Digital transformation in the logistics industry: An evidence-based synthesis of logistics activity. *TPM-Testing, Psychometrics, Methodology in Applied Psychology*, 32(2), 1081-1097.
- [25] Rafiq-uz-Zaman, M. (2022). Redesign for 21st-century skills: Preparing learners for a rapidly changing workforce. *Journal of Business Insight and Innovation*, 1(2), 89-102.
- [26] Taofeek, A., Hamzah, F., Liang, W., Peterson, M. B., Rajuroy, A., & Adekola, P. (2025). Developing Dynamic Vocational Training Frameworks Through Sustained Industry Collaboration: A Strategic Approach to Workforce Readiness.
- [27] Rao, S. G., Bakshi, P., & Bhoola, V. (2025). Human Capital and Technology Factors in IT Outsourcing Success: A Socio-Technical Perspective. *Library of Progress-Library Science, Information Technology & Computer*, 45(2).
- [28] Aithal, P. S. (2023). Enhancing industrial automation through efficient technology management in society. *International Journal of Applied Engineering and Management Letters (IJAEML)*, 7(4), 184-215.
- [29] Tenakwah, E. S., & Watson, C. (2025). Embracing the AI/automation age: preparing your workforce for humans and machines working together. *Strategy & Leadership*, 53(1), 32-48.
- [30] Benayoune, A., Hamid, A. A., Rahman, N. S. F. A., Kalbani, K. A., & Slimi, Z. (2021). Logistics 4.0 skills requirements: evidence from a developing country. *Canadian Journal of Business and Information Studies*, 4(2), 24-36.
- [31] Phinla, W., Phinla, W., & Mahapoonyanont, N. (2025). Universities as Learning Ecosystems: Strategic Pathways to Lifelong Learning in the 21st Century.
- [32] Brunello, G., Rückert, D., Weiss, C., & Wruuck, P. (2023). Advanced digital technologies and investment in employee training: Complements or substitutes? (No. 2023/01). EIB Working Papers.
- [33] Lozano-Almansa, J. M., Fernández, J. T., & Sanchez-Perez, A. M. (2023). Digital transformation and real options: Evaluating the investment in Cloud ERP. *Engineering Economics*, 34(4), 397-411.
- [34] Trenerry, B., Chng, S., Wang, Y., Suhaila, Z. S., Lim, S. S., Lu, H. Y., & Oh, P. H. (2021). Preparing workplaces for digital transformation: An integrative review and framework of multi-level factors. *Frontiers in Psychology*, 12, 620766.
- [35] Nguyen, D. K., Broekhuizen, T., Dong, J. Q., & Verhoef, P. C. (2023). Leveraging synergy to drive digital transformation: A systems-theoretic perspective. *Information & Management*, 60(7), 103836.
- [36] Ye, D., Xu, B., Wei, B., Zheng, L., & Wu, Y. J. (2024). Employee work engagement in the digital transformation of enterprises: a fuzzy-set qualitative comparative analysis. *Humanities and Social Sciences Communications*, 11(1), 1-15.
- [37] Fukuda, K. (2020). Science, technology and innovation ecosystem transformation toward society 5.0. *International Journal of Production Economics*, 220, 107460.
- [38] Kroh, J., & Schultz, C. (2023). The more the better? The role of stakeholder information processing in complex urban innovation projects for green transformation. *International Journal of Project Management*, 41(3), 102466.

- [39] Jewer, J., & Van Der Meulen, N. (2022). Governance of Digital Transformation: A Review of the Literature. In HICSS (pp. 1-10).
- [40] Constantiou, I., Joshi, M., & Stelmaszak, M. (2023). Organizations as digital enactment systems: A theory of replacement of humans by digital technologies in organizational scanning, interpretation, and learning. *Journal of the Association for Information Systems*, 24(6), 1770-1798.
- [41] Nas, A. (2025). Bridging the Quantum Divide: Global and Corporate Strategies in the Age of Quantum Technology.
- [42] Gerçek, A. A. (2024). Global and Local Forces Shaping Quantum Technology Development: Insights from the Researcher Perspective (Master's thesis, Middle East Technical University, Turkey).

Quantum Technology Readiness Among Higher Education Institution Students: Future Skills Perspective

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ABSTRACT — Quantum technology is increasingly recognised as a transformative technology that will reshape industries, digital innovation, and future workforce requirements. Consequently, higher education institutions are expected to prepare students with the competencies required to thrive in quantum-enabled environments. However, empirical evidence on the factors influencing students' quantum technology readiness remains limited, particularly in developing countries, and little is known about the mediating role of learning motivation in this relationship. This study examines the effects of digital competency, innovation mindset, and future skills readiness on quantum technology readiness, with learning motivation as a mediating variable. Grounded in the Technology Acceptance Model and Human Capital Theory, a quantitative survey was conducted among 400 undergraduate and postgraduate students from Malaysian HEIs. The data were analysed using SPSS 29 and covariance-based structural equation modelling with AMOS 29. The findings reveal that innovation mindset and future skills readiness significantly enhance quantum technology readiness, whereas digital competency has no direct effect after learning motivation is introduced. Learning motivation significantly mediates all proposed relationships, fully mediating the effect of digital competency and partially mediating the effects of innovation mindset and future skills readiness. This study contributes an extension on existing technology readiness research and provides practical guidance for designing future-ready higher education ecosystems that support Industry 5.0 and the emerging quantum economy.

KEYWORDS: Quantum Technology Readiness; Digital Competency; Innovation Mindset; Future Skills Readiness.

I. INTRODUCTION

Quantum technology (QT) is one of the most promising technological frontiers of the Fourth Industrial Revolution (IR4.0) and has the potential to revolutionize computing, cybersecurity, communication systems, logistics optimization, healthcare analytics, and sustainable industrial development. National strategies in countries like China, the United States, Germany, Singapore, and Japan have been accelerated to boost technological competitiveness and the workforce's capabilities for the future [1]. As a consequence, higher education institutions (HEIs) are increasingly required to educate students with high-level digital skills,

interdisciplinary thinking, and the capacity to apply these skills to the quantum era. Yet, even with the swift pace of technological progress, there are gaps in digital literacy, innovation culture, and the development of future-oriented skills at many HEIs, which hinder their efforts to foster students' QT readiness [2]. This challenge is especially pertinent in developing economies, as HEIs continue to adjust to digital transformation agendas and Industry 5.0 education ecosystems [3].

Thus, digital competency has emerged as an essential prerequisite in today's HEI context, as students are expected to manage data systems, digital platforms, and intelligent technologies effectively. However, the digital confidence and exposure to higher-level computational technologies among HEI students remain low, especially in the fields related to QT systems and future applications of computing [4]. At the same time, there is a lack of an innovative mindset among students, stemming from a traditional teaching method that focuses on theoretical study without conducting experiments, fostering cross-disciplinary cooperation, or promoting technological innovation. This situation hinders students' readiness to embrace disruptive technologies and their readiness to participate in quantum industries. Moreover, the skills required for future readiness (critical thinking, problem-solving, adaptability, technological agility, and thinking about sustainability) have become more crucial in preparing students for the changing job market. Currently, according to, the curriculum at HEIs does not always fully incorporate these competencies into teaching and learning ecosystems.

Nevertheless, HEIs are increasingly investing in digital infrastructure and smart learning systems, but students' motivation to continue learning and exploring technology is not always consistent. According to [5], learning motivation is a key mediating factor because students with high intrinsic motivation are more inclined to accept technological change, engage in digital learning environments, and gain confidence in high-tech devices such as quantum computing and quantum communication systems. However, previous research, such as, has mainly focused on technological readiness at the infrastructural or institutional level, neglecting motivational and sustainability aspects of I. learning. As a result, students might be able to access digital

technologies but not be motivated to participate fully in digital technological ecosystems. This is a broader HEI problem that drives towards a technology-focused digital transformation, not a learner-focused one.

Based on the above discussion, the following research questions are proposed:

RQ1: How does digital competency influence students' readiness toward QTs?

RQ2: How does innovation mindset influence students' readiness toward QTs?

RQ3: How does future skills readiness influence students' readiness toward QTs?

RQ4: How does learning motivation mediate the relationship between digital competency, innovation mindset, future skills readiness, and QTs readiness?

The novelty of the study is the integration of a unified framework to explain the readiness of HEI students to QTs and contributes a student-centered orientation to readiness for QT and future digital ecosystems.

II. THEORETICAL FOUNDATION

This study is based on the Technology Acceptance Model (TAM) by [6] and the Human Capital Theory (HCT) by [7], which are complementary, as both explain the cross-field phenomenon of new technology acceptance. The combination of these theories offers a holistic view of the influence of technological, cognitive, and educational aspects on students' readiness towards QTs in HEIs. This is especially fitting because QT readiness encompasses not only HEI students' acceptance and perceptions of advanced technologies, but also the development of knowledge, skills, and competencies, as well as the learning capabilities needed for future digital economies. In HEI, TAM has been widely used to investigate the use of digital learning systems, artificial intelligence (AI) applications, virtual learning environments, and new educational technologies. TAM is relevant to this study because it explores the relationships among digital competency, an innovation mindset, students' readiness for future skills, and their perceptions and acceptance of QTs. The better students' digital competence, the greater their sense of the usefulness and manageability of QTs, the more prepared they are to enter a QT-based learning environment. Likewise, students with an innovative mindset are more likely to attempt out disruptive technologies and embrace new digital ecosystems. Higher levels of skills readiness are associated with stronger adaptability, problem-solving, critical thinking, and technological agility, further enhancing students' confidence in their ability to embrace more advanced technological systems. TAM therefore provides a solid theoretical basis for understanding the mechanisms underlying students' conduct and cognition that determine their readiness for QTs.

Aside from TAM, HCT stresses that education, training, competencies, and skills strengthen an individual's productivity and future economic value. HCT argues that national development and workforce competitiveness depend on acquiring knowledge, being technologically literate, and engaging in lifelong learning. For the purposes of this study, QT readiness is defined as a future orientation HCT that should be developed at HEIs to equip students for the new digital economies and Industry 5.0. Hence, digital

competency, innovativeness and readiness for future skills can be seen as human capital that will help students to become effective participants in the quantum-based industries. Therefore, this study is grounded in a strong theoretical foundation provided by the integration of TAM and HCT.

III. LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Figure 1 illustrates the conceptual framework, followed by the development of the study's hypotheses.

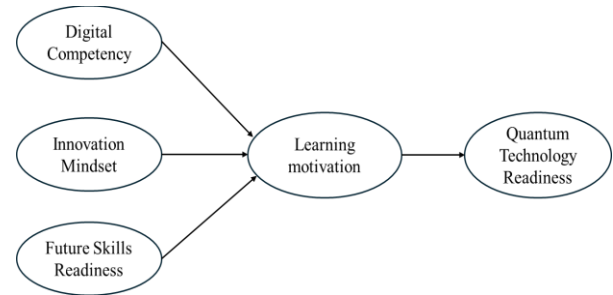


Figure 1. Conceptual Framework

Digital skills are essential for students to succeed in the modern educational and industrial contexts that rely on technology. Digital competency is demonstrated by students through the use of data systems, virtual platforms, and computational tools in their learning, communication, and problem-solving processes in their higher education institutions. Despite this, students need to develop solid digital competencies to acquire knowledge and skills to interact with and participate in complex technological systems, as QTs increasingly become part of digital ecosystems. Recent studies [8] have found that students with stronger digital competencies are more confident, flexible, and ready for new technologies, due to their familiarity with digital interfaces, computational thinking, and technology-based learning environments. Consequently, digital competency enhances students' technological self-efficacy and opens them to understanding quantum computing, quantum communication, and QT-based AI (QT-AI). Despite the fact that advanced quantum concepts require independent study, technological confidence, and flexibility of thought, students remain significantly unprepared to adapt to a changing digital environment, as they lack advanced technological learning systems.

H1: Digital competency positively influences students' QT readiness.

The use of a creative, experimental vision and the ability to think outside the box and solve problems proactively are key components of innovative thinking in technology and education. An innovation mindset is gaining significance in universities as they become increasingly digital and must think inter-disciplinarily, be technologically adaptable, and always innovative. Innovative students have a higher chance of experimenting, learning, and adapting with disruptive technology. The study of QTs demands students to think out of the box because of their scientific complexity, non-classical computational approaches and applications in industry. Recent studies, such as [9], on educational and technological transformation reveal that an innovative student is more likely to use advanced technologies and

future-oriented digital systems. Students who are more focused on innovation are more readily accepting of new technologies as a learning opportunity. Thus, an innovation mindset facilitates students to experiment with disruptive technologies such as quantum computers and quantum communications. Furthermore, HEI digital transformation focuses on innovation-driven learning ecosystems, fostering creativity, interdisciplinary collaboration, and technological experimentation.

H2: Innovation mindset positively influences students' QT readiness.

Students' ability to learn and apply skills in a rapidly changing technological or industrial environment is future skills readiness. These skills include critical thinking, adaptability, digital collaboration, problem-solving, technological agility, creativity, and lifelong learning. As industries move towards Industry 5.0, HEIs are required to prepare their students with the skills needed to be relevant in the future, dynamic workforce ecosystem. QTs need graduates who can think across disciplines, be robustly computational and are technology learners. It is essential for QTs, where students need to be acquainted with the complicated concepts of computation and future QTs. Furthermore, HCT considers skills readiness a key human capital investment, which enhances students' productivity, employability and technological adaptability for the future [10]. Graduates with future skills readiness are contributing to workforce development and the national digital transformation. Nonetheless, many HEIs find it difficult to incorporate competencies relevant to the future into their curricula, leading to a disconnect between what is taught in institutions and what employers expect. Inadequate skills development can undermine students' confidence and readiness for future technologies.

H3: Future skills readiness positively influences students' QT readiness.

Students are motivated by their drive, enthusiasm and desire to engage in learning and technological education. According to [11], the learning motivation impacts on the persistence, technological exploration and knowledge of college students. Students who are willing to learn embrace digital learning, explore new technology and take on advanced skills. Furthermore, learning motivation is an indispensable component of QTs, which involve constant learning, thinking and technological curiosity. Students need to keep their technological knowledge current for QT readiness, to fit the evolving digital landscape. Motivation contributes to the complexity and uncertainty of learners' confidence in technology. Recent educational technology studies show that learning motivation strongly impacts students' technological readiness, digital engagement, and innovation. Motivated students can use digital learning platforms more effectively, engage in technological activities together, and learn at their own pace to enhance future technological capabilities as HEIs are digitally transformed. Learning motivation contributes to the development of digital competency, an innovation mindset, readiness for future skills, and readiness for QTs.

H4: Learning motivation positively influences students' QT readiness.

The motivation has a significant impact on students' perseverance, involvement and adaptation to new technologies. The readiness of students for the implementation of QTs in HEIs is not affected by their digital skills, digital skills orientation, or future skills, but rather by their willingness and motivation to learn and become acquainted with more sophisticated technological concepts. To be part of technology-driven learning ecosystems, students need to be intrinsically motivated, as QTs involve complex computational systems, interdisciplinary knowledge, and rapidly changing digital applications [12]. If the students have digital skill or future-oriented skill but have a lack of motivation to learn, they might feel disinterested in participating in an educational system that uses a lot of technology. This is important because QT students are expected to enter new technology fields and face disruptive technological systems.

Furthermore, motivation driven by technical challenges encourages innovation-minded students to learn technology, as they are able to explore and create in the process [13]. Furthermore, future skills readiness encourages students to learn and strive to grow as students who are adaptable, future-oriented, and technologically agile. Therefore, students with motivation are more apt to use technology enhanced learning systems and become tech ready and more adaptable. The relationship between learning motivation, digital competency and innovation mindset, and readiness for students' future skills in QT can be mediated.

H5a: Learning motivation mediates the relationship between digital competency and QT readiness.

H5b: Learning motivation mediates the relationship between innovation mindset and QT readiness.

H5c: Learning motivation mediates the relationship between future skills readiness and QT readiness.

IV. METHODOLOGY

The unit of analysis of this study comprises students at the undergraduate and postgraduate levels from Malaysian public and private HEIs registered with the Ministry of Higher Education Malaysia. Prior to main data collection, the questionnaire was pre-tested with three academics who specialize in educational technology, digital transformation, and higher education studies, alongside two industry professionals with the ecosystems of emerging technologies and digital innovation. The questionnaire items were checked by these experts to assess their clarity, relevance, appropriateness and comprehensibility to ensure consistency between the measurement and the constructs being assessed. A pilot study with 30 HEI students was conducted in line with the recommendation of [14]. The Cronbach alpha value for all five variables was found to be above the criterion value of .70, which means there was a good level of reliability and internal consistency of the items on each of the variables.

The Krejcie and Morgan Sample Size Determination Table was used to determine the sample size for this study [15]. This study focused on 400 HEI students to reduce sampling error and enhance the statistical strength, as they are spread across various HEIs in Malaysia. Questionnaires distributed through Google Form via the internet, the university's communications and digital academic networks.

The data collection was carried out for about 16 weeks (about 4 months). In addition, the research ethics committee granted ethical clearance for this study prior to data collection. The voluntary participation, anonymity, data confidentiality, and the right to withdraw from the study at any time without risk of penalty were explained to the respondents.

In view of construct measurement, the questionnaire consists of six sections: Demographic details, Digital competency, Innovation mindset, Future skills readiness, Learning motivation and QT readiness. The following measurement items were rated on a 5-point Likert scale, from strongly disagree to strongly agree.

The descriptive statistics of HEI students were analysed by using SPSS version 29. The reliability and validity of the measurement model were tested using confirmatory factor analysis (CFA) according to the two-step procedure by [16]: first, assessing reliability, and second, assessing validity. This CFA procedure was employed to evaluate the measurement items and to make sure that the constructs obtained acceptable convergent validity, discriminant validity, and internal consistency reliability. In addition, Harman's single-factor test was used to examine the common-method bias. The result showed that the first factor accounted for only 48.7% of the total variance, which is less than 50%. Hence, common-method bias was not deemed a problem in this study. The direct relationships among the study's variables were then analyzed using covariance-based structural equation modeling (CB-SEM) AMOS. Besides, the structural model analysis was conducted to test the proposed hypotheses, and the significance and strength of the relations between variables of the study were determined. Lastly, the significance of the indirect effects in the context of the research was assessed using 5000 resamples to test the mediation.

V. ANALYSIS AND FINDINGS

A. Respondents' Demographic Profile

Table 1 presents the demographic characteristics of the respondents involved in this study.

Table 1 Respondent's Profile

Demographic Variable	Frequency	Percentage (%)
Gender		
Male	214	53.5
Female	186	46.5
Age Group		
18–21 years	145	36.3
22–25 years	189	47.3
Above 25 years	66	16.5
Type of Institution		
Government University	228	57.0
Private University	172	43.0
Level of Study		
Bachelor Degree	331	82.8
Postgraduate	69	17.2
Field of Study		
Science and Technology	152	38.0
Engineering	91	22.8
Business and Management	84	21.0
Social Sciences	73	18.2

Demographic results showed that the majority (53.5%) of the respondents were male students, and the females (46.5%) were also in the majority. The majority of respondents were 22-25 years old (47.3%), indicating that they were mostly

young adults actively involved in digital learning ecosystems and emerging technological environments. Government universities had the largest share at 57.0%, followed by private universities at 43.0%. The majority of the respondents (82.8%) were under the bachelor's degree level, while the remaining 17.2% were at the postgraduate level. This suggests that the results mainly reflect undergraduate students' views on the readiness of QTs and future digital skills. As for academic fields, the largest group of respondents was from science and technology (38.0%), followed by engineering (22.8%), business and management (21.0%), and social sciences (18.2%). The results indicate that the study identified participants with a wide range of academic backgrounds in digital transformation and future technological systems.

B. Descriptive Analysis

The descriptive analysis indicate that the respondents generally demonstrated moderate to high levels of digital competency, innovation mindset, future skills readiness, learning motivation, and QT readiness. The highest mean was the learning motivation ($M = 3.95$), which showed that students were very enthusiastic to learn and be involved in the use of new technologies. However, QT readiness had the lowest mean score ($M = 3.79$), indicating students' positive technology readiness, but there is still potential to further enhance their readiness to support technological ecosystems in the QT field. The correlation analysis also showed that all variables were positively correlated and were significantly correlated with each other.

C. Confirmatory Factor Analysis (CFA)

The results demonstrated that the measurement model achieved satisfactory goodness-of-fit values. The model fitness indices were $\chi^2 = 1582.417$, $df = 1216$, $\chi^2/df = 1.301$, $GFI = 0.912$, $AGFI = 0.901$, $CFI = 0.981$, $NFI = 0.943$, and $RMSEA = 0.028$. These values suggest that the measurement model is a good fit for the observed data. Cronbach's alpha, composite reliability (CR), average variance extracted (AVE) and factor loadings were then used to test the reliability and validity of the constructs. Table 2 shows the reliability and validity results.

Table 2 Reliability and Validity of Constructs

Variable	Indicator	Factor Loading	Cronbach Alpha	Composite Reliability (CR)	Average Variance Extracted (AVE)
Digital Competency	DC1	0.78	0.892	0.905	0.617
	DC2	0.81			
	DC3	0.79			
	DC4	0.84			
	DC5	0.76			
	DC6	0.77			
Innovation Mindset	IM1	0.82	0.901	0.912	0.632
	IM2	0.79			
	IM3	0.84			
	IM4	0.86			
	IM5	0.74			
	IM6	0.77			
Future Skills Readiness	FSR1	0.83	0.907	0.918	0.648
	FSR2	0.85			
	FSR3	0.87			
	FSR4	0.74			
	FSR5	0.79			
	FSR6	0.78			

Learning Motivation	LM1	0.84	0.911	0.920	0.655
	LM2	0.81			
	LM3	0.88			
	LM4	0.79			
	LM5	0.83			
	LM6	0.76			
Quantum Technology Readiness	QTR1	0.85	0.916	0.924	0.669
	QTR2	0.87			
	QTR3	0.89			
	QTR4	0.78			
	QTR5	0.80			
	QTR6	0.77			

The factor loadings of all measures were significant ($p < 0.001$), as well as within the acceptable limits. Since the results revealed high values of construct reliabilities and significant factor loadings, the convergent validity of the model is confirmed [17]. Furthermore, the average variance extracted (AVE) values were higher than 0.5 and composite reliability was higher than the AVE values. Hence, these results again confirmed the convergent validity model.

D. Discriminant Validity

The discriminant validity was also assessed and, suggested that the AVE value of every construct should be greater than the squared correlation coefficient with other constructs. Table 3 confirmed the discriminant validity. Further, the values of the maximum shared variance (MSV) and average shared variance (ASV) were combined with the AVE values. If all the ASV and MSV values are recorded less than their respective AVE values, discriminant validity prevails.

Table 3 Discriminant Validity					
Variables	1	2	3	4	5
Digital Competency	0.785				
Innovation Mindset	0.372	0.795			
Future Skills Readiness	0.336	0.435	0.805		
Learning Motivation	0.397	0.462	0.504	0.809	
Quantum Technology Readiness	0.325	0.384	0.476	0.533	0.818

E. Structural Equation Modeling (SEM)

Figure 2 illustrates the structural model and the hypotheses were tested using CB-SEM AMOS. The results of the comparison of the three structural models (direct effects model, full mediation model, and partial mediation model) are shown in Table 5. The findings indicate that the partial mediation model demonstrated the best goodness-of-fit indices with $\chi^2/df = 1.257$, GFI = 0.912, AGFI = 0.901, CFI = 0.986, NFI = 0.944, and RMSEA = 0.027. All of these values were above the recommended thresholds, indicating good model fitness. The partial mediation model was ultimately adopted as the structural model in this study.

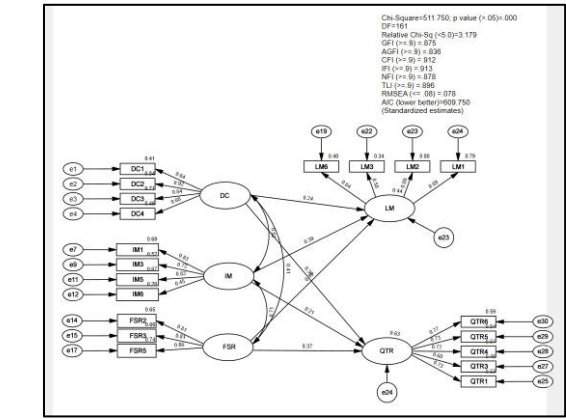


Figure 2. Structural Model.

Table 4 Fit Indices of Structural Models								
Model	χ^2	χ^2/df	$\Delta\chi^2$	GF	AG	CF	NF	RMS
Direct Effects Model	1874.225	1.5	-	0.8	0.88	0.9	0.9	0.036
Full Mediation Model	1542.118	1.2	332.1	0.9	0.89	0.9	0.9	0.028
Partial Mediation Model	1526.774	1.2	15.34	0.9	0.90	0.9	0.9	0.027

Note: $\Delta\chi^2$ represents discrepancies between the model and the following model. ***p-value < 0.001.

Structural Relationship	Direct Effects Model	Full Mediation Model	Partial Mediation Model	Hypothesis Decision
H1: Digital Competency → Quantum Technology Readiness	0.19 (3.42**)	—	0.05 (0.88)	Not Supported
H2: Innovation Mindset → Quantum Technology Readiness	0.31 (5.87***)	—	0.14 (2.64**)	Supported
H3: Future Skills Readiness → Quantum Technology Readiness	0.34 (6.22***)	—	0.12 (2.11*)	Supported
Digital Competency → Learning Motivation	—	0.33 (5.74***)	0.31 (5.46***)	—
Innovation Mindset → Learning Motivation	—	0.35 (6.61***)	0.34 (6.72***)	—
Future Skills Readiness → Learning Motivation	—	0.38 (7.03***)	0.36 (7.28***)	—
H4: Learning Motivation → Quantum Technology Readiness	—	0.79 (13.88***)	0.49 (7.21***)	Supported

Note: *p < 0.05; **p < 0.01; ***p < 0.001. Values in parentheses represent t-values.

Table 6 shows the standardized path coefficients of the structural model. The results showed that innovation mindset ($\beta = 0.14$, $p < 0.01$) and future skills readiness ($\beta = 0.12$, $p < 0.05$) have positive effects on QT readiness, which is useful for supporting H2 and H3. But once learning motivation was added to the model, the direct effect of digital competency on QT readiness was not significant ($\beta = 0.05$, $p > 0.05$), indicating that H1 was not supported in the final model. The results also showed that Digital competency, Innovation mindset, and Future skills readiness have a significant impact on learning motivation. Moreover, learning motivation positively affects the QT readiness ($\beta = 0.49$, $p < 0.001$), which helps to support the H4. The results in general support the importance of learning motivation in enhancing students' readiness for emerging QTs.

F. Mediation Analysis

Bootstrapping analysis with 5,000 resampling was used to examine the mediation effects of Learning Motivation. Bootstrapping procedures were used to assess the significance of the indirect effects among the study constructs. The results showed that learning motivation significantly mediated the relationships between digital competency, innovation mindset, future skills readiness, and QT readiness. Results of the mediation analysis are displayed in Table 6.

Table 6 Mediation Analysis Results

Mediation Relationship	Indirect Effect	Result
H5a: Digital Competency → Learning Motivation → Quantum Technology Readiness	0.118***	Full Mediation
H5b: Innovation Mindset → Learning Motivation → Quantum Technology Readiness	0.167***	Partial Mediation
H5c: Future Skills Readiness → Learning Motivation → Quantum Technology Readiness	0.176***	Partial Mediation

Note: ***p-value < 0.001.

The results suggest that building high-level learning motivation through digital competence increases the students' readiness for QTs. In summary, the mediation results indicate the importance of the concept of learning motivation in enhancing technological readiness and preparedness of students in the future quantum-informed digital environments in HEIs.

VI. DISCUSSION

In view of RQ1, this study showed that the concept of digital competency does not directly affect the final structural model of students' readiness for QT. The relationship between digital competency and the direct effect on QT readiness was significant, but became non-significant after adding the learning motivation. The result shows that digital competency alone is not sufficient to directly enhance students' readiness for advanced technologies such as QT systems, if students lack strong motivation for continuous learning and technological exploration. The result is consistent with recent studies suggesting that students' digital competencies are not necessarily correlated with their technological readiness when adequate learning engagement and motivation support are absent [18]. The results, however,

are inconsistent with the latest studies by [19], which found that digital competency has a direct positive impact on readiness for disruptive technologies and emerging digital ecosystems. The present study, however, builds upon these arguments, showing that QT readiness is more demanding than general technological readiness as it demands greater cognitive involvement, learning commitment, and a higher level of motivation to persist. This outcomes confirmed that knowledge competence is not the only component of students' readiness for QTs, but also a high level of motivation for learning activities in the context of digitally transforming higher education ecosystems.

Pertaining to RQ2, the results indicated that the relationship between the innovation mindset and students' QT readiness is positive and significant. This shows that students with a more innovative type of thinking, an open attitude to experimentation, creativity, and adaptability to technological change are better equipped to interact with future QTs and digital transformation ecosystems. This discovery aligns with recent studies highlighting the strong association between innovation and technological experimentation, digital exploration, and adaptation of emerging technologies [20]. The findings also validate the assumption of the TAM, which states that the positive perception and openness towards innovation have a positive impact on the acceptance and readiness of technological use among its users. However, a few recent studies suggested that the ability to innovate is not enough to explain technological readiness because other factors, such as institutional technological infrastructure and digital support systems, also play a role in technological adaptation among students [21]. The findings confirms the idea that thinking innovatively is a strategic psychological ability that increases students' readiness for the emerging technological ecosystems of the quantum era.

The results of RQ3 showed that future skills readiness has a significant, positive influence on students' QT readiness. It shows that the level of students' readiness for future-oriented competencies, such as adaptability, critical thinking, technological agility, creativity, and problem solving, is associated with the students' readiness for QTs and future digital ecosystems. This finding is consistent with recent research that asserts future competencies to prepare the workforce center on the ability to adapt to disruptive digital technologies and technological ecosystems that span disciplines [22, 23]. The results also corroborate the HTC, suggesting that investments in future skills increase people's technological competitiveness, their employability, and their adaptability to new technologies. Therefore, these findings highlights the significance of competencies with a future outlook in fostering students' readiness for future quantum-driven educational and industrial ecosystems.

In view of RQ4, the results showed that learning motivation is a significant mediator in reinforcing students' readiness in QT. Specifically, the relationships between digital competency and QT readiness, between innovation mindset and QT readiness, and between future skills readiness and QT readiness are partially mediated by learning motivation, and the relationship between digital competency and QT readiness is fully mediated. The results show that students' competencies and future-oriented capabilities are more effective in improving readiness for QT when they are highly motivated to continuously learn about technology. Students with high learning motivation are more likely to

maintain technological learning behavior, actively engage in high-level technological environments, and integrate into rapidly changing digital environments.. These indicates that, students' motivation, may face barriers to adopting new technologies due to insufficient institutional infrastructure and limited access to them. Notwithstanding these arguments, the current study shows that students' motivation to learn remains a strong predictor of their future-oriented capacities and competencies regarding QT readiness [24, 25], confirming that the mechanism of motivational learning is necessary to enhance students' preparedness for the future, namely in the educational and technological ecosystem driven by quantum.

VII. IMPLICATIONS OF THE STUDY

A. Theoretical Implications

Firstly, the study extends the TAM by incorporating the concepts of digital competency, innovation mindset, readiness for future skills and motivation to learn in the context of QT readiness.. Secondly, the results show that students' orientation towards QTs is shaped not only by their perceptions of technologies but also by various cognitive, motivational, and future competencies. This helps build on the existing literature, highlighting the need to develop multidimensional explanatory mechanisms for emerging technological readiness, in addition to the traditional technology acceptance variables. Thirdly, the study introduces a conception of digital competency, innovation mindset, and readiness for future skills as strategic human capital dimensions required for future technological economies. The results strengthen the view that HEIs are the key to building technologically understanding human capital that will help drive the economic ecosystems of the quantum age and Industry 5.0.

B. Policy Implications

With countries' growing interest and investment in new technologies such as QTs, AI, and advanced digital infrastructure, policymakers should not only understand and care about the importance of investing in infrastructure but also about the readiness of the next generation of human resources. Hence, national educational policies should place emphasis on embedding future-oriented technological competencies in higher education systems to support sustainable workforce preparation. An important policy implication is to rethink higher education policies for the era of Industry 5.0 and emerging QT ecosystems. In most developing nations, current education policies still focus on high school academics rather than higher-order digital literacy. It is therefore recommended that policymakers put in place a national policy and strategy to promote exposure to quantum, computational thinking, digital innovation competencies, and technology across various fields of science and engineering in the academic curriculum. In addition, governments should invest more in digital transformation projects, smart learning infrastructure, and new technology laboratories to enable students to gain hands-on experience with complex technology systems. Therefore, policymakers should promote educational reform that encourages student-centered learning, innovation ecosystems, and technology-based educational engagement.

C. Higher Education Institution Implications

The results show that students' self-perception of digital competency, innovation mindset, readiness for future skills, and learning motivation significantly affect their readiness for QTs. As a result, HEIs must realize that it is not enough to support the technological ecosystems of the future by simply delivering digital infrastructure as they must create comprehensive learning environments that reinforce technological adaptability, innovation capacity, and continuous learning engagement. A significant consequence for HEIs is the need to restructure curricula to reflect emerging technology trends and the future market's needs. The classical education approach, with its strong emphasis on theoretical instruction, might not be adequate to address the unprecedented technological challenges posed by quantum computers and high-tech digital systems. Therefore, HEIs should conduct interdisciplinary digital learning, develop computational thinking, and conduct innovation-based projects, and provide students with quantum-related exposure in academic programs. This curricular change can help build students' technological confidence and prepare them better for the future, while aligning with expectations for education in Industry 5.0.

D. Student Implications

The study clearly illustrates how the four factors of digital competency, innovation mindset, future skills readiness, and learning motivation play a significant role in the readiness of students for QT. A key outcome for students is the need to be more technologically competent than merely competent with technology. Hence, students need to be actively involved in technology-related learning experiences, computational and skills-building, and digital learning experiences in a proactive manner to prepare them for future technological environments. As students build digital skills, they can become more confident and flexible in dealing with new technologies such as quantum systems. The results also indicate that adopting an "innovation mindset" is important for future career sustainability. Students who are willing to experiment, be creative, and explore technology will be better prepared to embrace new, disruptive technologies. Therefore, students should embrace new learning experiences grounded in innovation, interdisciplinary practice, and problem-solving, with an emphasis on technology development, to be creative and adaptable.

VIII. LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Although the study has contributed to understanding students' readiness at HEIs for QT, it has some limitations that should be recognized. First, the study used a cross-sectional research design, that is, data were gathered at one time. The findings offer insightful information on the relationships between digital competency, innovation mindset, readiness for future skills, learning motivation, and readiness for QT, but do not allow for causal relationships or changes in students' readiness over time. Hence, future research is recommended to adopt longitudinal designs to study students' readiness across all levels of education and during technological transitions towards QTs. Second, the study was conducted with only students from government and private universities, and this may not allow the findings to be generalized to other educational settings like technical and vocational education and training (TVET) institutes,

community colleges, and secondary education. Except for a few, each educational institution could have different technological infrastructure, technological environments, and curriculum integration related to emerging technologies. Future study should therefore build on this agenda, extending it to other educational contexts and comparing it with international settings to yield broader insights into QT readiness across learning ecosystems.

IX. CONCLUSION

This study investigated the effects of digital competency, innovation mindset, and future skills readiness on students' QT readiness in the context of HEIs, with learning motivation as the mediating factor. The results shed light on the broader applicability of the TAM and the HCT in students' readiness for disruptive technological ecosystems. Combining technological, cognitive, and motivational aspects within a single framework provides a more holistic view of how universities can prepare future-ready students for economies and Industry 5.0 driven by QTs. In practice, the results highlight the importance of bolstering digital learning ecosystems, innovative education approaches, and future skills development plans across HEIs and among policy and education stakeholders. In addition, policies in the field of education and institutional digital transformation should be supported by governments and educational policymakers, with the aim of connecting the national educational policies with the future needs of the technological workforce. The results of this study indicate that the preparation of QT readiness is not solely dependent on technology infrastructure but also on students' competencies, innovative orientation, skills readiness for the future, and motivation for continuous learning.

REFERENCES

- [1] L. Paglieri, A. Bonomi Savignon, F. Scalabrini, and L. Costumato, "Navigating the quantum frontier: examining government strategy to the next technological revolution. Transforming Government: People," *Process and Policy*, vol. 19, no. 4, pp. 700–724, 2025.
- [2] M. F. J. Fox, B. M. Zwickl, and H. J. Lewandowski, "Preparing for the quantum revolution: What is the role of higher education?," *Phys. Rev. Phys. Educ. Res.*, vol. 16, no. 2, 2020.
- [3] D. L. Fekete and A. Kiss, "Toward building smart contract-based higher education systems using zero-knowledge Ethereum virtual machine," *Electronics (Basel)*, vol. 12, no. 3, p. 664, 2023.
- [4] V. T. T. Nguyen and H.-L. Chen, "Examining impacts of information system success and perceived stress on students' self-regulated learning mediated by intrinsic motivation in online learning environments: second-order structural equation modelling analyses," *Educ. Inf. Technol. (Dordr.)*, pp. 1–24, 2023.
- [5] Shard, D. Kumar, and S. Koul, "Digital transformation in higher education: A comprehensive review of e-learning adoption," *Hum Syst Manage*, vol. 43, no. 4, pp. 433–454, 2024.
- [6] F. D. Davis, "Perceived usefulness, perceived ease of use, and user acceptance of information technology," *Manag. Inf. Syst. Q.*, vol. 13, no. 3, pp. 319–340, 1989.
- [7] G. S. Becker, "Nobel lecture: The economic way of looking at behavior," *J. Polit. Econ.*, vol. 101, no. 3, pp. 385–409, 1993.
- [8] E. Kučera and O. Haffner, "Competency-based hybrid learning: A modern approach to teaching programming and digital technologies subjects," *IEEE Access*, 2025.
- [9] V. Shabunina, O. Labenko, A. Horbachenko, T. Tsuprun, and O. Sydorenko, "Technologies and Innovations in the Educational Process: Experience of the University of the Future. Futurity Education," vol. 4, pp. 145–168, 2024.
- [10] Y. Wei, "Developing students' creativity and critical thinking in higher education: A human capital theory perspective," in *Advances in Social Science, Education and Humanities Research*, Paris: Atlantis Press SARL, 2025, pp. 52–61.
- [11] P. Whig, P. Sharma, and A. A. Elngar, *Quantum learning: Bridging artificial intelligence, quantum computing, and data science in education*. CRC Press, 2026.
- [12] Y. J. P. Bautista, "Bridging education and entrepreneurial digital transformation: Cultivating digital literacy and innovation," in *Signals and Communication Technology*, Cham: Springer Nature Switzerland, 2026, pp. 183–198.
- [13] I. Sellami, H. Amin, O. Ozturk, A. Zaman, S. D. Sever, and E. Tok, "Digital, localised and human-centred design makerspaces: Nurturing skills, values and global citizenship for sustainability," *Discover Education*, vol. 4, no. 1, p. 28, 2025.
- [14] J. Dinis-Carvalho and S. Fernandes, "Applying lean concepts to teaching and learning in higher education: Findings from a pilot study," *International Journal of Engineering Education*, vol. 33, no. 3, pp. 1048–1059, 2017.
- [15] R. V. Krejcie and D. W. Morgan, "Sample size determination table," *Educational and Psychological Measurement*, vol. 30, no. 3, pp. 607–610, 1970.
- [16] Baharum, H., Ismail, A., Awang, Z., McKenna, L., Ibrahim, R., Mohamed, Z., & Hassan, N. H. (2023). The study adapted instruments based on Confirmatory Factor Analysis (CFA) to validate measurement models of latent constructs. *International Journal of Environmental Research and Public Health*, 20(4), 2860.
- [17] K. Dyer, "The Disproportionate Burden of International K. G. Jöreskog, "Testing structural equation models," *Sage Focus Editions*, vol. 154, pp. 294–294, 1993.
- [18] R. Chaudhuri, S. Chatterjee, P. D. Vrontis, and F. Vicentini, "Effects of human capital on entrepreneurial ecosystems in the emerging economy: the mediating role of digital knowledge and innovative capability from India perspective," *J. Intellect. Cap.*, vol. 24, no. 1, pp. 283–305, 2023.
- [19] M. Malekpour, M. Sedighi, F. Caboni, V. Basile, and C. Troise, "Exploring digital transformation and technological innovation in emerging markets," *Int. J. Emerg. Mark.*, vol. 20, no. 13, pp. 96–121, 2025.
- [20] J. K.-U. Brock and A. K. Kohli, "The emerging world of digital exploration services," *J. Bus. Res.*, vol. 155, no. 113434, p. 113434, 2023.
- [21] A. M. Sayaf, M. M. Alamri, M. A. Alqahtani, and W. M. Alrahmi, "Factors influencing university students' adoption of digital learning technology in teaching and learning," *Sustainability*, vol. 14, no. 1, Art. no. 493, 2022.
- [22] W. McKinley, "Doomsdays and new dawns: Technological discontinuities and competence ecosystems," *Acad. Manag. Perspect.*, vol. 36, no. 2, pp. 729–743, 2022.
- [23] A. Shore and T. Dinning, "Developing student's skills and work readiness: an experiential learning framework," *J. Work-appl. Manag.*, vol. 15, no. 2, pp. 188–199, 2023.
- [24] X. Li, J. Zhang, and J. Yang, "The effect of computer self-efficacy on the behavioral intention to use translation technologies among college students: Mediating role of learning motivation and cognitive engagement," *Acta Psychol. (Amst.)*, vol. 246, no. 104259, p. 104259, 2024.
- [25] D. Dong, "Self-determination theory perspectives on the influence of digital learning engagement on motivation in extracurricular learning activities: Considering the mediating role of digital self-efficacy," *Learn. Motiv.*, vol. 90, no. 102135, p. 102135, 2025.

Comparative Effectiveness of Video- and Leaflet-Based Health Education on Mothers' Knowledge of Acute Respiratory Infection Prevention Among Children Under Five in a Rural Community Health Setting in Aceh, Indonesia

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ABSTRACT

Background: Acute Respiratory Infection (ARI) is one of the leading causes of morbidity and mortality among children under five years of age. Mothers' knowledge plays a crucial role in preventing ARI. Educational media, such as videos and leaflets, can be utilized as health promotion tools to improve mothers' knowledge regarding ARI prevention among under-five children.

Objective: This study aimed to determine and compare the effectiveness of video- and leaflet-based educational media in improving mothers' knowledge of ARI prevention among under-five children at Garot Integrated Health Post, Darul Imarah, Aceh Besar District.

Methods: This study employed a quasi-experimental design using a two-group pretest-posttest approach. The study involved 58 mothers with under-five children, who were divided into two groups: the video education group and the leaflet education group, with 29 participants in each group. Participants were selected using a purposive sampling technique. Data were collected using a knowledge questionnaire administered before and after the intervention. Data were analyzed using the Wilcoxon Signed-Rank Test and the Mann-Whitney U Test.

Results: Both educational interventions significantly improved mothers' knowledge regarding Acute Respiratory Infection (ARI) prevention among children under five. In the video group, the mean knowledge score increased from 59.14 to 94.31, while in the leaflet group, it increased from 63.10 to 96.72. The Wilcoxon Signed-Rank Test demonstrated statistically significant improvements in knowledge within both groups ($p < 0.001$). However, the Mann-Whitney U test indicated no statistically significant difference in effectiveness between the two educational media ($p = 0.165$), suggesting that both interventions produced comparable improvements in maternal knowledge.

Conclusion: Video- and leaflet-based health education were equally effective in improving mothers' knowledge regarding ARI prevention among children under five. These findings support the use of either educational medium in community-based health

promotion programs, particularly in rural Integrated Health Posts and other resource-limited primary healthcare settings, where the selection of educational media should be based on local resources and implementation feasibility rather than differences in educational effectiveness.

Keywords: Acute Respiratory Infection (ARI), mothers' knowledge, educational media, video, leaflet, under-five children

I. INTRODUCTION

Acute Respiratory Infection (ARI) remains a major public health problem and is one of the leading causes of morbidity and mortality among children under five years of age worldwide. According to the World Health Organization (WHO) (2023), ARI is an infection affecting the respiratory tract and may be caused by viruses, bacteria, or fungi. This disease is among the leading causes of death in children under five, particularly in developing countries.

In Indonesia, ARI continues to be a significant public health concern requiring serious attention. Data from the Indonesian Ministry of Health (2023) indicate that ARI is among the ten most common diseases treated at primary healthcare facilities. Children under five are particularly vulnerable to ARI due to their immature immune systems, which make them more susceptible to infections.

The high incidence of ARI among under-five children is influenced by various factors, including nutritional status, household crowding, housing ventilation, exposure to cigarette smoke, immunization status, and parents' knowledge regarding disease prevention. Dagne *et al.* (2020) reported that low maternal knowledge is associated with an increased risk of ARI among children because of inadequate preventive health practices.

Mothers play a crucial role in maintaining child health, particularly in recognizing early symptoms of illness, maintaining environmental hygiene, fulfilling nutritional needs, and seeking appropriate healthcare services when necessary. A study conducted by Anteneh and Hassen (2020) found that mothers with adequate knowledge were more likely to implement ARI preventive measures than those with lower levels of knowledge.

Improving public knowledge can be achieved through various health promotion activities. Health promotion is designed to empower individuals and communities to maintain and improve their health status. According to Notoatmodjo (2018), health education is one of the most effective strategies for improving health-related knowledge, attitudes, and behaviors.

Educational media are commonly used to disseminate health information. The selection of appropriate educational media can significantly influence the effectiveness of the learning process and information acceptance among target populations. Commonly used educational media include leaflets and videos because they are easily accessible and capable of delivering health information effectively (Harerimana *et al.*, 2016).

Leaflets are printed educational materials that provide concise, clear, and easy-to-understand information. Their advantages include portability, the ability to be read repeatedly, and relatively low production costs. Fitriani (2017) stated that leaflets can improve audience understanding because the information can be reviewed independently at any time.

In addition to leaflets, video-based educational media are widely used in health education because they combine visual and auditory elements simultaneously. According to Arsyad (2019), videos can enhance participants' attention, interest, and understanding by presenting information in a more engaging and comprehensible manner than printed media.

A study conducted by Qasim, Nugrawati, and Juwita (2024) demonstrated that health education interventions significantly improved public knowledge regarding ARI prevention ($p = 0.000$). These findings highlight the important role of health education in enhancing community understanding of disease prevention measures. Several previous studies have demonstrated that both video- and leaflet-based health education effectively improve public knowledge regarding various health problems, including Acute Respiratory Infection (ARI). However, most of these studies were conducted in hospitals, schools, or urban communities where access to healthcare services, educational facilities, and digital technology is relatively adequate. Consequently, evidence regarding the comparative effectiveness of these educational media in rural community-based primary healthcare settings remains limited.

According to data from the Darul Imarah Community Health Center (2024), the number of ARI cases has increased over the past three years, while preliminary observations indicated that many mothers still had limited knowledge regarding ARI prevention. Considering the limited evidence comparing educational media within rural community health settings in Aceh, this study aimed to

compare the effectiveness of video- and leaflet-based health education in improving mothers' knowledge regarding ARI prevention among children under five attending Garot Integrated Health Post, Darul Imarah, Aceh Besar District, Indonesia. The novelty of this study lies in evaluating the implementation of two commonly used educational media within a rural Integrated Health Post setting, thereby providing practical evidence to support the selection of appropriate health education strategies for resource-limited primary healthcare services.

II. METHODS

This study employed a quantitative approach using a quasi-experimental two-group pretest–posttest design to compare the effectiveness of video- and leaflet-based educational media on mothers' knowledge regarding the prevention of Acute Respiratory Infection (ARI) among children under five. The study was conducted at Garot Integrated Health Post, Darul Imarah Subdistrict, Aceh Besar District, Indonesia, in May 2025. The study population consisted of mothers with children under five years of age who attended the Integrated Health Post during the study period. A total of 58 eligible respondents were recruited using a purposive sampling technique because only mothers who met the predefined inclusion criteria and were willing to participate in the educational intervention were considered suitable for the study objectives. The respondents were equally allocated into two intervention groups: the video education group ($n = 29$) and the leaflet education group ($n = 29$).

Data were collected using a structured questionnaire adopted from a previously validated instrument assessing mothers' knowledge regarding ARI prevention among children under five. The questionnaire consisted of items covering the definition, causes, signs and symptoms, modes of transmission, prevention, and early home management of ARI. Since the instrument was adopted from a previously validated questionnaire, its content validity and reliability had been established in the original study. The questionnaire was administered before (pre-test) and after (post-test) the intervention. The first group received health education through video-based media, whereas the second group received the same educational content using leaflet-based media.

This study was guided by Mayer's Cognitive Theory of Multimedia Learning, which explains that educational media facilitate knowledge acquisition through cognitive processing of visual and auditory information. Data were analyzed using descriptive (univariate) statistics to summarize respondents' demographic characteristics and knowledge scores. Inferential (bivariate) analysis was performed using the Wilcoxon Signed-Rank Test to evaluate changes in knowledge before and after the intervention within each group, while the Mann–Whitney U Test was used to compare the effectiveness of the two educational media. Statistical significance was established at $p < 0.05$.

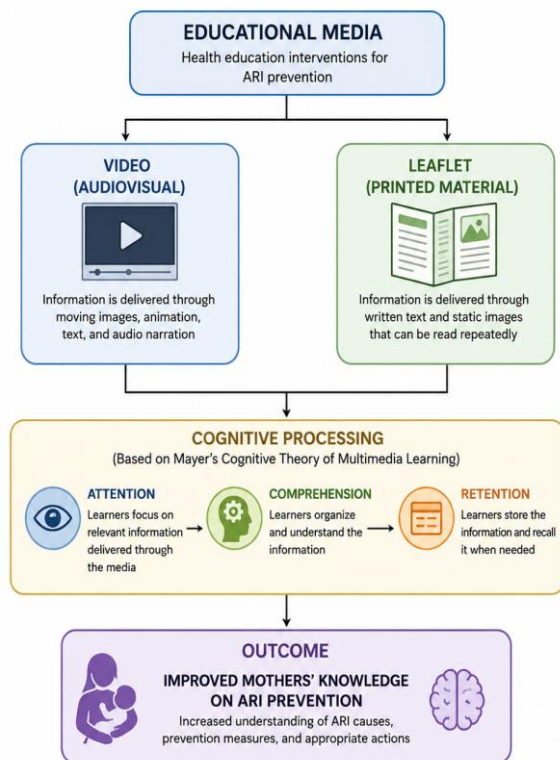


Figure 1. Conceptual Framework Based on Mayer's Cognitive Theory of Multimedia Learning.

III. RESULTS

Based on the study conducted among 29 respondents in each group, the following results were obtained:

Table 1 Baseline Characteristics of Respondents

Characteristics	Video Group (29)	Leaflet Group (29)	Total
Age Category, n (%)			
Early Adulthood	18 (62.1)	10 (34.5)	28 (48.3)
Productive Adulthood	10 (34.5)	17 (58.6)	27 (46.6)
Late Adulthood	1 (3.4)	2 (6.9)	3 (5.3)
Occupation, n (%)			
Employed	10 (34.5)	11 (37.9)	21 (36.2)
Unemployed/Housewife	19 (65.5)	18 (62.1)	37 (63.8)
Education Level, n (%)			
Higher Education	5 (17.2)	8 (27.6)	13 (22.4)
Secondary Education	14 (48.3)	10 (34.5)	24 (41.4)

Primary Education	10 (34.5)	11 (37.9)	21 (36.2)
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Table 1 presents the baseline characteristics of respondents in both intervention groups. Among mothers in the video group, most respondents were in the early adulthood category (62.1%), whereas the majority of respondents in the leaflet group were classified as productive adults (58.6%). Regarding occupation, most respondents in both groups were unemployed or housewives, accounting for 65.5% in the video group and 62.1% in the leaflet group. In terms of educational attainment, secondary education was the most common level in the video group (48.3%), while respondents in the leaflet group were relatively evenly distributed across educational levels, with the highest proportion having primary education (37.9%). Overall, the demographic characteristics of respondents were relatively comparable between the two intervention groups.

Table 2 Mean Scores of Mothers' Knowledge Based on Educational Media

Groups	n	Mean	Median	Min-Max	Std. Dev
Video Education Group (Pretest)	29	59.1	60.00	40-80	9.456
Video Education Group (Posttest)	29	94.31	95.00	80-100	6.778
Leaflet Education Group (Pretest)	29	63.10	65.00	45-75	6.778
Leaflet Education Group (Posttest)	29	96.72	100.00	80-100	5.049

Table 2 summarizes mothers' knowledge scores before and after the interventions. The average knowledge score in the video group increased from 59.14 ± 9.46 before the intervention to 94.31 ± 6.78 after the intervention. Likewise, the leaflet group showed an increase from 63.10 ± 7.95 to 96.72 ± 5.05 . Overall, both educational media were associated with substantial improvements in mothers' knowledge regarding ARI prevention among children under five.

Table 3 Comparison of Mothers' Knowledge Before and After the Educational Interventions

Groups	Pretest Mean±SD	Posttest Mean±SD	Mean Difference	P-Value
Video	59.14 ± 9.46	94.31 ± 6.78	35.17	0.000

Leaflet	63.10 ± 7.95	96.72 ± 5.05	33.62	0.000
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As presented in Table 3, mothers' knowledge significantly improved following both educational interventions. In the video group, the mean knowledge score increased by 35.17 points, whereas the leaflet group demonstrated an increase of 33.62 points. The Wilcoxon Signed-Rank Test showed statistically significant improvements in both groups ($p < 0.001$), indicating that each educational medium effectively enhanced mothers' knowledge regarding ARI prevention.

Table 4 Comparison of the Effectiveness of Video and Leaflet Educational Media

Outcome	Video	Leaflet	Mann-Whitney U	Z	P-Value
Mean Rank	26.67	32.33	338.50	-1.389	0.165

Table 4 compares the effectiveness of the two educational media. Although the leaflet group obtained a slightly higher mean rank (32.33) than the video group (26.67), the Mann-Whitney U test indicated that the difference was not statistically significant ($U = 338.50$; $Z = -1.389$; $p = 0.165$). These findings suggest that both educational media were equally effective in improving mothers' knowledge regarding ARI prevention among children under five.

IV. DISCUSSION

The present study demonstrated that both video- and leaflet-based health education significantly improved mothers' knowledge regarding the prevention of Acute Respiratory Infection (ARI) among children under five. Mothers in the video group showed an increase in mean knowledge scores from 59.14 before the intervention to 94.31 after the intervention, while mothers in the leaflet group showed an increase from 63.10 to 96.72. The Wilcoxon Signed-Rank Test confirmed that these improvements were statistically significant in both groups ($p < 0.001$). These findings indicate that both educational media effectively enhanced mothers' understanding of ARI prevention.

The substantial improvement observed after the intervention highlights the important role of health education in increasing maternal knowledge. Before receiving the intervention, many mothers had limited knowledge regarding the causes, transmission, and preventive measures of ARI. After participating in the educational sessions, respondents demonstrated a better understanding of disease prevention strategies, indicating that structured educational interventions can effectively improve health literacy among caregivers of young children.

Video-based education proved to be effective because it combines visual and auditory stimulation, allowing participants to receive information through multiple sensory channels simultaneously. Educational videos are able to illustrate disease transmission, symptoms, and preventive

practices more clearly than verbal explanations alone. This multisensory learning process enhances attention, facilitates comprehension, and improves information retention. Consequently, mothers who received video-based education experienced a marked improvement in their knowledge after the intervention.

Similarly, leaflet-based education also resulted in a significant increase in knowledge. Printed educational materials allow mothers to read the information repeatedly at their own pace, making it easier to review important messages whenever necessary. This flexibility enables respondents to reinforce their understanding after the educational session has ended. Although leaflet-based education relies primarily on reading ability, the concise presentation of information accompanied by illustrations can effectively improve comprehension and knowledge retention.

When the effectiveness of the two educational media was compared using the Mann-Whitney U test, no statistically significant difference was found between the video and leaflet groups ($p = 0.165$). Although the leaflet group achieved a slightly higher mean rank than the video group, the difference was not statistically significant. This finding suggests that both educational media provide comparable benefits in improving mothers' knowledge regarding ARI prevention. Therefore, healthcare providers may select either educational medium according to available resources, logistical considerations, and the preferences of the target population.

The findings of this study are consistent with previous research demonstrating that health education interventions significantly improve parental knowledge regarding childhood disease prevention. Qasim *et al.* (2024) reported that health education significantly increased community knowledge regarding ARI prevention. Likewise, Harerimana *et al.* (2016) concluded that both audiovisual and printed educational media effectively improve health-related knowledge when educational content is delivered systematically and according to participants' educational backgrounds. The present findings further support these studies by demonstrating that both educational approaches can successfully improve maternal knowledge in community-based health promotion settings.

V. CONCLUSION AND RECOMMENDATIONS

This study demonstrated that both video- and leaflet-based health education effectively improved mothers' knowledge regarding the prevention of Acute Respiratory Infection (ARI) among children under five. Significant improvements in knowledge were observed in both intervention groups following the educational sessions. However, no statistically significant difference was found between the effectiveness of the two educational media, indicating that both video and leaflet interventions provide comparable educational benefits.

These findings suggest that both educational media can be effectively incorporated into community-based health promotion programs to improve maternal knowledge of ARI prevention. The choice of educational media may therefore

be determined by the availability of resources, implementation setting, and the characteristics and preferences of the target population, rather than by differences in educational effectiveness.

Healthcare providers, particularly those working in community health centers and integrated health posts, are encouraged to integrate both video- and leaflet-based education into routine maternal and child health promotion activities. The use of diverse educational media may enhance community engagement and strengthen disease prevention efforts among families with children under five.

Future research is recommended to include larger and more diverse study populations, employ probability sampling methods, and assess additional outcomes such as changes in attitudes, preventive practices, long-term knowledge retention, and the incidence of ARI among children under five. Such studies would provide a more comprehensive evaluation of the effectiveness and sustainability of health education interventions.

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REFERENCES

- [1] World Health Organization. Acute respiratory infections in children [Internet]. Geneva: World Health Organization; 2023 [cited 2026 Jun 17]. Available from: <https://www.who.int>
- [2] Kementerian Kesehatan Republik Indonesia. Profil Kesehatan Indonesia Tahun 2023. Jakarta: Kementerian Kesehatan RI; 2024.
- [3] Kementerian Perencanaan Pembangunan Nasional. Tujuan Pembangunan Berkelanjutan (Sustainable Development Goals/SDGs) Indonesia. Jakarta: Bappenas; 2021.
- [4] Dagne H, Andualem Z, Dagnew B, Tadesse A. Acute respiratory infection and associated factors among under-five children in Ethiopia: a community-based cross-sectional study. *BMC Pediatr*. 2020;20(1):93.
- [5] Anteneh ZA, Hassen HY. Determinants of acute respiratory infection among children under five years of age in Ethiopia. *BMC Pediatr*. 2020;20(1):1-9.
- [6] Harerimana A, Mtshali NG, Mukamana D. Educational media in health promotion: effectiveness of audiovisual and printed media in improving health knowledge. *Afr J Nurs Midwifery*. 2016;18(2):45-53.
- [7] Notoatmodjo S. Promosi Kesehatan dan Perilaku Kesehatan. Edisi Revisi. Jakarta: Rineka Cipta; 2018.
- [8] Arsyad A. Media Pembelajaran. Edisi ke-23. Jakarta: Rajawali Pers; 2019.
- [9] Fitriani S. Promosi Kesehatan. Yogyakarta: Graha Ilmu; 2017.
- [10] Qasim YI, Nugrawati N, Juwita H. Pengaruh penyuluhan kesehatan terhadap peningkatan pengetahuan masyarakat tentang pencegahan infeksi saluran pernapasan akut. *J Kesehat Masy*. 2024;12(1):45-52.
- [11] UPTD Puskesmas Darul Imarah. Laporan Tahunan Program Pencegahan dan Pengendalian ISPA Tahun 2024. Aceh Besar: UPTD Puskesmas Darul Imarah; 2024

**EMPOWERMENT OF *ASNAF* THROUGH
ARTIFICIAL INTELLIGENCE**

Reskilling and Upskilling Pesantren's Educators in Digital Transformation

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ABSTRACT — This study examines the strategic role of digital learning platforms in supporting the sustainable reskilling and upskilling of pesantren educators amid the rapid advancement of Artificial Intelligence (AI), learning analytics, and other emerging digital technologies. Using a qualitative literature review approach, the study critically synthesizes evidence from peer-reviewed journal articles, policy documents, institutional reports, and other relevant scholarly sources to explore the opportunities, challenges, and strategic implications of digital transformation in Islamic boarding schools. The thematic analysis reveals four major findings. First, digital learning platforms—including Learning Management Systems (LMS), cloud-based learning services, adaptive technologies, and AI-assisted instructional tools—significantly enhance educators' digital literacy, pedagogical innovation, collaborative learning, and continuous professional development. Second, sustainable competency development is strengthened through flexible and collaborative digital learning ecosystems that facilitate lifelong learning. Third, the implementation of digital transformation remains constrained by unequal digital infrastructure, limited technological readiness, inconsistent policy implementation, and socio-cultural resistance to innovation. Finally, successful digital transformation requires not only technological adoption but also strategic leadership, effective governance, ethical AI integration, and continuous institutional capacity building. Based on these findings, this study proposes a Digital Competency Framework for Pesantren Educators that integrates digital competency development, collaborative learning ecosystems, institutional governance, ethical AI implementation, and continuous professional learning within the context of Education 5.0 and Society 5.0. The proposed framework contributes to the growing literature on digital transformation in Islamic education and provides practical guidance for policymakers, educational leaders, and pesantren administrators in designing sustainable digital capacity-building initiatives.

KEYWORDS: Digital Transformation, Digital Learning Platforms, Pesantren Education, Digital Competency Framework, Education 5.0.

I. INTRODUCTION

The rapid advancement of Artificial Intelligence (AI), learning analytics, and other emerging digital technologies has significantly transformed the global educational landscape, creating new expectations for educators' competencies and institutional adaptability. In this context, figdigital learning platforms have emerged as strategic

instruments for supporting continuous professional development, particularly in educational environments that require adaptive responses to technological disruption [1]. As traditional Islamic educational institutions, pesantren are increasingly challenged to integrate digital innovations while preserving their cultural identity, educational values, and pedagogical traditions.

Despite the growing adoption of Learning Management Systems (LMSs), cloud-based learning services, and AI-assisted instructional tools, the process of digital transformation within pesantren remains uneven. While these technologies have demonstrated considerable potential to enhance educators' digital literacy, pedagogical innovation, and collaborative learning practices, their implementation is frequently constrained by inadequate digital infrastructure, limited technological readiness, insufficient institutional support, and socio-cultural resistance to change [2]. Furthermore, inconsistencies in policy implementation continue to hinder the sustainable integration of digital technologies into educator professional development systems.

Existing literature has extensively examined digital transformation in mainstream education systems. However, relatively limited attention has been given to how Islamic educational institutions, particularly pesantren, strategically develop educators' digital competencies through sustainable reskilling and upskilling initiatives. Previous studies have primarily focused on technology adoption, digital infrastructure, or isolated professional development programs, with comparatively little emphasis on integrating educational policy, pedagogy, technological readiness, institutional leadership, and ethical AI governance into a comprehensive framework tailored to the unique characteristics of pesantren. This research gap highlights the need for a holistic conceptual framework capable of guiding digital transformation while preserving the institutional values, culture, and educational mission of Islamic boarding schools [3].

Therefore, this study aims to examine the strategic role of digital learning platforms in supporting the sustainable reskilling and upskilling of pesantren educators through a qualitative literature review. Beyond synthesizing existing knowledge, the study contributes to the literature by proposing a Digital Competency Framework for Pesantren

Educators, which integrates five interrelated dimensions: (1) digital competency development, (2) digital learning ecosystem, (3) institutional leadership and governance, (4) ethical Artificial Intelligence (AI) integration, and (5) continuous professional learning. The proposed framework makes both theoretical and practical contributions. Theoretically, it extends existing perspectives on digital transformation in Islamic education by integrating multiple dimensions into a unified conceptual model. Practically, it provides a strategic reference for policymakers, educational leaders, and pesantren administrators in designing sustainable digital capacity-building initiatives. The conceptual framework developed in this study is presented in Figure 1.

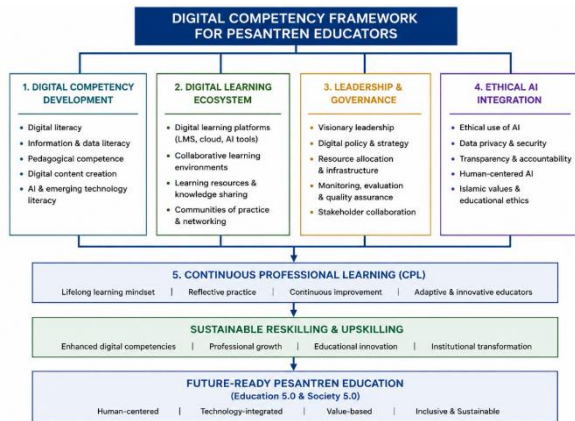


Figure 1. Conceptual Framework.

II. LITERATURE REVIEW

This study is grounded in an integrated theoretical framework that explains how digital learning platforms support the sustainable reskilling and upskilling of pesantren educators in the context of Education 5.0 and Society 5.0. Rather than viewing these theories independently, the study positions them as complementary perspectives that collectively explain the process of digital transformation in Islamic boarding schools. The conceptual relationship begins with educators' acceptance of digital technologies, followed by competency development, collaborative knowledge construction, and ultimately the achievement of sustainable educational transformation [4].

The Technology Acceptance Model (TAM) provides the foundation for understanding educators' willingness to adopt digital learning platforms [5]. According to TAM, technology is more likely to be accepted when users perceive it as useful and easy to use. In the context of pesantren, Learning Management Systems (LMS), cloud-based applications, and AI-assisted learning technologies can improve instructional effectiveness, simplify teaching activities, and enhance learning experiences. Therefore, successful digital transformation depends not only on technological availability but also on educators' perceived usefulness, perceived ease of use, and readiness to integrate digital technologies into teaching practices [6].

Building upon technology acceptance, Human Capital Theory explains that investments in education, training, and professional development enhance individual competencies and institutional performance. Digital learning platforms function as strategic tools for strengthening pedagogical

competence, digital literacy, AI literacy, and instructional innovation among pesantren educators. Continuous reskilling and upskilling enable educators to adapt to technological change while improving the quality and competitiveness of Islamic education [7].

The learning process enabled by digital platforms is further explained through Socio-Constructivist Learning Theory, which emphasizes that knowledge is constructed through collaboration, interaction, and shared learning experiences. Digital learning environments facilitate online discussions, collaborative projects, communities of practice, and knowledge sharing among educators. These collaborative processes encourage reflective practice, peer learning, and continuous professional development while maintaining the educational values and traditions of pesantren [8].

These three theoretical perspectives are situated within the broader paradigms of Education 5.0 and Society 5.0, which advocate human-centered education supported by advanced digital technologies, including Artificial Intelligence (AI), learning analytics, and intelligent digital ecosystems. Within these paradigms, educators are expected not only to master digital technologies but also to demonstrate creativity, critical thinking, ethical responsibility, collaboration, and lifelong learning competencies. Consequently, digital transformation in pesantren requires the integration of technological readiness, continuous competency development, collaborative learning, institutional leadership, and value-based educational principles [9].

Based on this integrated theoretical perspective, the study proposes that sustainable reskilling and upskilling of pesantren educators are achieved through the interaction of five key dimensions: (1) technology acceptance, (2) human capital development, (3) collaborative knowledge construction, (4) institutional support aligned with Education 5.0 and Society 5.0, and (5) continuous professional learning. These dimensions form the conceptual foundation for the proposed Digital Competency Framework for Pesantren Educators, which guides the analysis presented in this study. The relationships among these theoretical perspectives are illustrated in Figure 2.

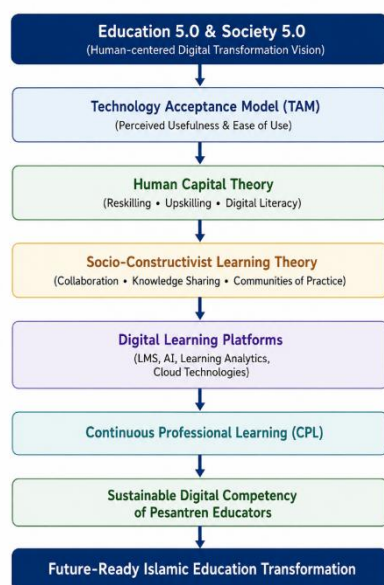


Figure 2. Five Key Dimensions.

This study employs a qualitative literature review to examine the strategic role of digital learning platforms in supporting the reskilling and upskilling of pesantren educators amid rapid digital transformation. The review integrates policy analysis and case-based evidence reported in previous studies to develop a comprehensive understanding of digital learning implementation in Islamic boarding schools.

The study relies exclusively on secondary data sources, including peer-reviewed journal articles, government regulations, institutional reports, academic books, conference proceedings, and international policy documents related to digital learning, Education 5.0, Society 5.0, Artificial Intelligence (AI) in education, digital competency development, and the transformation of Islamic education.

Documents were identified through searches in Scopus, Web of Science, Google Scholar, ERIC, and ScienceDirect using combinations of keywords such as digital learning, pesantren education, Islamic education, Education 5.0, Artificial Intelligence in education, teacher reskilling, and teacher upskilling. The literature search focused primarily on publications published between 2020 and 2026, while several seminal works published before 2020 were retained to provide theoretical foundations.

The selection of documents followed predefined inclusion and exclusion criteria. Documents were included if they (1) discussed digital learning or digital transformation in education; (2) addressed teacher professional development, reskilling, or upskilling; (3) focused on Islamic education or comparable educational settings; (4) were published in peer-reviewed journals or by reputable institutions; and (5) were available in full text. Documents were excluded if they were duplicated, lacked academic credibility, were unrelated to the research objectives, or provided insufficient methodological information [10].

Following the screening process, approximately relevant sources were selected for in-depth analysis. The selected literature was analyzed using thematic analysis, following an iterative process to ensure transparency and replicability. First, all documents were read repeatedly to achieve data familiarization. Second, meaningful statements related to digital learning implementation, educator competency

development, policy support, technological innovation, and institutional challenges were identified and coded. Third, similar codes were grouped into broader categories, from which major themes were generated. Fourth, the themes were reviewed and refined by continuously comparing findings across different sources to ensure consistency and conceptual coherence. Finally, the themes were interpreted in relation to the study objectives and existing theoretical frameworks, including the Technology Acceptance Model (TAM), Human Capital Theory, Socio-Constructivist Learning Theory, Education 5.0, and Society 5.0 [11].

To enhance the trustworthiness of the review, the study employed source triangulation by comparing evidence from scholarly publications, policy documents, and institutional reports. An audit trail documenting the literature selection, coding, and theme development was maintained throughout the analysis to improve transparency, consistency, and reproducibility.

III. RESULT AND DISCUSSION

The thematic analysis of selected documents identified four major themes that explain the strategic role of digital learning platforms in supporting the reskilling and upskilling of pesantren educators. These themes consistently emerged across peer-reviewed journal articles, government policy documents, institutional reports, and conference proceedings, indicating a strong convergence of evidence regarding digital transformation in Islamic education.

Theme 1. Digital Learning Platforms as Enablers of Educator Competency Development

The first theme demonstrates that digital learning platforms serve as the primary mechanism for strengthening educators' professional competencies. Across the reviewed literature, Learning Management Systems (LMS), cloud-based learning environments, AI-assisted instructional tools, and learning analytics were consistently identified as technologies that enhance digital literacy, pedagogical competence, instructional innovation, and educators' ability to design student-centered learning. Rather than merely providing access to technology, these platforms facilitate continuous competency development through self-paced learning, online certification, virtual mentoring, and professional learning communities.

Theme 2. Continuous Professional Learning through Digital Ecosystems.

The second theme indicates that sustainable reskilling and upskilling depend on the availability of collaborative digital learning ecosystems. The analyzed studies consistently report that online training, webinars, digital resource repositories, discussion forums, and communities of practice enable educators to engage in continuous professional learning regardless of geographical location. The literature further emphasizes that collaborative learning environments promote knowledge sharing, peer support, and reflective practice, thereby strengthening educators' adaptability to technological change.

Theme 3. Institutional and Policy Support as Critical Success Factors

The third theme emerging from the literature highlights the importance of institutional leadership and policy support in facilitating digital transformation. Evidence from policy documents and previous studies suggests that successful implementation depends on strategic leadership, adequate digital infrastructure, governance mechanisms, and institutional commitment to professional development. Conversely, recurring barriers identified across the literature include unequal technological infrastructure, limited digital competencies among educators, inconsistent policy implementation, financial constraints, and socio-cultural resistance to educational innovation.

Theme 4. Integrating Artificial Intelligence within Education 5.0 and Society 5.0

The fourth theme reveals that Artificial Intelligence (AI) is increasingly viewed as an enabler of personalized learning, adaptive professional development, and data-informed educational decision-making. However, the reviewed studies consistently emphasize that AI adoption should be accompanied by ethical governance, digital inclusion, and alignment with Islamic educational values. Sustainable digital transformation therefore requires balancing technological innovation with institutional culture, educational ethics, and human-centered learning principles promoted by Education 5.0 and Society 5.0.

The synthesis of these four themes indicates that sustainable reskilling and upskilling of pesantren educators cannot be achieved through technology adoption alone. Instead, the literature demonstrates that digital competency development results from the interaction among digital learning platforms, institutional leadership, policy support, collaborative professional learning, and ethical AI integration. These interrelated themes form the empirical basis of the Digital Competency Framework for Pesantren Educators, proposed in this study to guide future digital transformation initiatives in Islamic boarding schools.

IV. CONCLUSION

This study demonstrates that digital learning platforms play a strategic role in supporting the sustainable reskilling and upskilling of pesantren educators amid the rapid advancement of digital technologies, Artificial Intelligence (AI), and the paradigms of Education 5.0 and Society 5.0. Through a qualitative literature review, the thematic analysis identified four interrelated themes that collectively shape successful digital transformation in Islamic boarding schools: (1) digital learning platforms as enablers of educator competency development, (2) continuous professional learning through collaborative digital ecosystems, (3) institutional leadership and policy support as critical success factors, and (4) ethical AI integration within human-centered educational transformation.

The findings suggest that sustainable digital transformation cannot be achieved solely through the adoption of digital technologies. Instead, it requires the integration of educator digital competency development, supportive institutional governance, collaborative learning environments, continuous professional learning, and ethical AI implementation that aligns with the values and

educational traditions of pesantren. These interconnected dimensions reinforce the importance of adopting a holistic approach to digital transformation in Islamic education.

The primary contribution of this study is the development of a Digital Competency Framework for Pesantren Educators, which integrates five strategic dimensions: digital competency development, digital learning ecosystems, institutional leadership and governance, ethical AI integration, and continuous professional learning. The framework extends existing perspectives on digital transformation in Islamic education by providing a coherent conceptual model that links technology adoption with educator capacity building and institutional transformation. From a practical perspective, the framework offers strategic guidance for policymakers, educational leaders, and pesantren administrators in designing sustainable digital capacity-building initiatives that are responsive to future educational challenges.

This study is limited by its reliance on secondary data derived from the existing literature and policy documents. Consequently, the proposed framework has not yet been empirically validated in diverse pesantren contexts. Future research is therefore recommended to examine and validate the proposed framework through qualitative case studies, quantitative surveys, or mixed-methods research involving pesantren educators and institutional stakeholders. Such empirical investigations will strengthen the applicability and generalizability of the framework and contribute to evidence-based digital transformation strategies in Islamic education.

REFERENCES

- [1] I. A. H. P. Albert, "Sustainable Islamic Education Learning With Connectivism Approach," *HIKMAH: Jurnal Pendidikan Islam*, vol. 1, no. 1, pp. 81-90, 2024.
- [2] D. R. G. D. Vaughan, *Blended Learning in Higher Education: Framework, Principles, and Guidelines*, New Jersey: Wiley Press Room, 2028.
- [3] T. W. S. Bates, "Can Artificial Intelligence Transform Higher Education?," *International Journal of Educational Technology in Higher Education*, vol. 17, no. 1, pp. 1-12, 2020.
- [4] A. Z. Natsir, "Evaluasi Program Pesantren Ramah Anak Model CIPP di Provinsi Sumatera Barat," *SURAU: Journal of Islamic Education*, vol. 1, no. 1, pp. 66-76, 2023.
- [5] A. G. Fred D. Davis, *The Technology Acceptance Model: 30 Years of TAM*, Berlin: Springer Nature, 2024.
- [6] C. Graham, *Current Research in Blended Learning*, Oxford: Taylor&Francis, 2019.
- [7] N. Selwyn, *Education and Technology: Key Issues and Debates*, London: Bloomsbury Publishing, 2021.
- [8] J. M. S. Y. Ronghuai Huang, *Educational Technology: A Primer for the 21st Century*, Singapore: Springer, 2019.
- [9] C. Redecker, *DigCompEdu, European Framework for the Digital Competence of Educators*, Luxembourg: Publications Office of the European Union, 2017.
- [10] G. Siemens, "Connectivism: A Learning Theory for Digital Age," *International Journal of INstructional Technology and Distance Learning*, vol. 2, no. 1, pp. 3-10, 2005.
- [11] L. D. Deng, "Deep Learning: Methods and Applications," *Foundation and Trends in Signal Processing*, vol. 7, no. 3, pp. 197-387, 2014.

Beyond Platform Popularity: A Strategic Platform Fit Perspective on Digital Marketing Platform Selection Among Asnaf Entrepreneurs

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ABSTRACT — *The rapid advancement of digital technologies has expanded marketing opportunities for asnaf entrepreneurs through various digital platforms, including TikTok, Facebook, Instagram, WhatsApp Business, and e-commerce platforms. However, the diversity of platform characteristics, user demographics, communication formats, and operational mechanisms has made platform selection increasingly complex. This study aims to examine the factors influencing digital marketing platform selection among asnaf entrepreneurs from the perspective of Strategic Platform Fit. A qualitative multiple-case study design was employed, involving eight respondents comprising three asnaf entrepreneurs, three zakat officers, and two digital marketing academics. Data were collected through semi-structured interviews and analysed using thematic analysis. The findings reveal three key factors influencing platform selection: platform suitability to target users, platform capability in reaching and generating customers, and platform compatibility with the type and characteristics of products or services offered. The study further demonstrates that asnaf entrepreneurs tend to select platforms that effectively reach relevant customer segments, enhance business discoverability through search and algorithmic mechanisms, and communicate product or service value through appropriate content formats. Theoretically, this study extends the digital marketing literature by highlighting the relevance of the Strategic Platform Fit perspective, which emphasises the alignment between platform characteristics, customer needs, and business offerings in shaping platform selection decisions. Practically, the findings provide useful insights for zakat institutions and entrepreneurship development agencies in designing more targeted and context-specific digital marketing support programmes to enhance the sustainability and competitiveness of asnaf-owned businesses.*

KEYWORDS: *Asnaf entrepreneurs; digital marketing; platform selection; strategic platform fit; target customers; entrepreneurship development.*

I. INTRODUCTION

Entrepreneurship among asnaf has increasingly gained attention as an important strategy in Malaysia's poverty alleviation agenda and the economic empowerment of the ummah, particularly through the implementation of productive zakat programmes that extend beyond the provision of financial assistance alone (1), (2), (3) State zakat institutions have implemented various initiatives, including business capital assistance, entrepreneurship training,

equipment provision, and business development support to help asnaf become more self-reliant and competitive in contemporary economic activities. Although some asnaf entrepreneurs have successfully increased their income and graduated from zakat recipient status, many continue to face challenges in expanding their businesses within an increasingly competitive and dynamic economic environment (4), (5).

The advancement of digital technology has transformed the business marketing landscape through the adoption of various platforms such as TikTok, Facebook, Instagram, Threads, WhatsApp Business, and e-commerce platforms. In Malaysia, the internet usage rate reached 98.0% in 2024, while internet coverage in populated areas exceeded 98.82% as of July 2025, indicating that the country's digital ecosystem has become increasingly developed and mature (6). This development has created greater opportunities for small and micro-entrepreneurs to enhance business visibility, reach customers, and expand market access through digital channels. In the context of asnaf entrepreneurs, digital marketing platforms have the potential to enable them to compete more effectively in the marketplace at a lower cost than traditional marketing channels.

Nevertheless, effective digital marketing is not solely dependent on access to technology or the availability of digital platforms. Many asnaf entrepreneurs continue to face constraints such as limited capital, low levels of digital literacy, and inadequate marketing experience in managing strategic marketing activities (4), (5). These challenges become more complex as each platform possesses distinct user characteristics, content formats, communication functions, and operational mechanisms. Furthermore, changes in platform algorithms, increasing competition for digital attention, and the need to maintain online visibility also affect the effectiveness of digital marketing platform utilisation (7), (8). As a result, entrepreneurs must not only adopt digital platforms but also determine which platforms are most suitable for their target customers, the products or services offered, and their business capabilities.

Although numerous studies have examined digital marketing among small enterprises and asnaf entrepreneurs, most have focused on technology adoption, social media usage, and the general effectiveness of digital marketing. Research explaining how entrepreneurs make decisions when

selecting specific platforms remains limited, particularly in understanding how customer characteristics, platform capabilities, and the nature of products or services are simultaneously considered in the platform selection process. This gap has resulted in a limited understanding of digital marketing platform selection, especially within the context of asnaf entrepreneurs who operate with constrained resources, skills, and business capacities.

Therefore, this study aims to examine the factors influencing digital marketing platform selection among asnaf entrepreneurs. Specifically, it focuses on how asnaf entrepreneurs evaluate and select platforms based on their suitability for target users, their capability to generate customers, and their compatibility with the products or services offered. Through a qualitative approach, this study seeks to contribute to a deeper understanding of the digital marketing platform selection process within the context of asnaf entrepreneurship, while also assisting zakat institutions and entrepreneurship development agencies in designing more targeted, contextualised, and effective digital marketing support initiatives.

II. LITERATURE REVIEW

A. Asnaf Entrepreneur Development in the Digital Economy Environment

The development of asnaf entrepreneurs through the productive zakat approach has increasingly been recognised as an important mechanism for reducing poverty and enhancing the socioeconomic mobility of low-income groups. Unlike traditional welfare assistance, which primarily focuses on addressing short-term needs, productive zakat emphasises the development of economic capacity through entrepreneurial activities capable of generating sustainable sources of income (9), (10). In line with this objective, various zakat institutions in Malaysia have implemented entrepreneurship development programmes encompassing business capital assistance, training, equipment provision, and business development support (3), (11), (2).

However, previous studies indicate that the success of asnaf entrepreneur development is not solely dependent on access to capital or entrepreneurship training. Rather, the ability to adapt to changes in market conditions and technological environments has emerged as a critical factor influencing business sustainability (5), (12). In the digital economy era, these changes have become increasingly significant as information search, customer interactions, and purchasing decisions are progressively shaped by digital platforms.

Although numerous studies have examined technology adoption and digital marketing among asnaf entrepreneurs, most have focused on issues related to technology acceptance, levels of social media usage, or the broader challenges of digital transformation (13), (14). Comparatively less attention has been given to how entrepreneurs make strategic decisions when selecting digital marketing platforms that best fit their business contexts. This limitation suggests that the understanding of platform selection as a strategic decision-making process remains insufficiently developed within the asnaf entrepreneurship development literature.

B. Digital Marketing and Platform Diversity

The advancement of digital technology has created an increasingly complex marketing ecosystem through the emergence of various platforms, including Facebook, Instagram, TikTok, WhatsApp Business, and e-commerce platforms. Each platform offers distinct functionalities, algorithms, content formats, and patterns of user interaction, thereby providing businesses with a wide range of strategic options (15), (16).

Previous studies generally suggest that the use of digital platforms can enhance business visibility, expand market reach, and strengthen customer relationships. However, findings regarding the most effective platforms remain inconclusive. Some studies emphasise the advantages of visual-based social media platforms such as TikTok and Instagram in increasing user engagement (17), (18), whereas other studies indicate that search-based and e-commerce platforms possess greater potential for generating purchase intentions and actual transactions (19), (20).

These contrasting findings suggest that platform effectiveness cannot be explained solely by platform characteristics. Rather, effectiveness is likely to depend on the degree of alignment between a platform and its specific context of use. Nevertheless, most existing studies continue to examine platforms in isolation and pay limited attention to how entrepreneurs compare, evaluate, and strategically select platforms. This gap highlights the need for a perspective capable of explaining the underlying logic of platform selection within real business contexts.

C. Platform Suitability for Target Users and Customer Generation

Changes in consumer behaviour within the digital environment have transformed the way customers search for information, evaluate alternatives, and make purchasing decisions. Consumers increasingly rely on various digital platforms as their primary source of information before making transactions, making marketing platforms a critical touchpoint between businesses and customers (15), (16). In this context, the effectiveness of a platform depends not merely on the size of its user base, but on the extent to which its users align with a business's target customers.

Previous studies have shown that factors such as user demographics, geographic location, interests, media consumption patterns, and preferences for specific content formats influence the effectiveness of a platform in delivering marketing messages (21), (22), (23). This perspective is consistent with the concept of audience alignment, which suggests that a platform can function optimally only when the characteristics of its users closely match the target customers of a business.

However, customer alignment alone is insufficient to explain platform effectiveness. In an increasingly algorithm-driven digital environment, discoverability, content recommendation systems, and information distribution mechanisms also influence a platform's ability to generate potential customers. Previous studies indicate that platforms differ in their capacity to attract new customers, retain existing customers, and connect businesses with consumers who possess stronger purchase intentions (19), (24).

Nevertheless, most existing studies examine customer alignment and customer-generation capability as two separate dimensions. Research that integrates these two

dimensions to explain strategic platform selection remains limited, particularly within the context of micro-enterprises and community-based entrepreneurs such as asnaf entrepreneurs. This gap highlights the need to understand how customer alignment and customer-generation capability interact in shaping digital marketing platform selection decisions.

D. Platform Suitability for the Type and Characteristics of Products or Services

In addition to customer-related factors, the effectiveness of digital marketing platforms is also influenced by the characteristics of the products or services being offered. Products and services differ in the way customers evaluate, understand, and develop confidence in the value proposition provided. Consequently, a platform that is suitable for one type of product may not necessarily be appropriate for another product or service.

Marketing literature suggests that certain products can be classified as *experience goods*, whereby their true value can only be assessed after consumption or use (25). In such cases, platforms that facilitate the communication of user experiences through visual content, demonstrations, and storytelling have been found to be more effective in influencing customer decision-making (26), (17), (18). In contrast, products that are more information-oriented may require different forms of communication to assist customers in making more rational evaluations.

In the service sector, the challenge becomes even more complex because customers typically face a higher degree of uncertainty prior to purchase (27), (28). Therefore, platforms that enable the demonstration of service processes, customer testimonials, and social proof are often regarded as more effective in enhancing customer trust in a particular service offering (29), (30).

Although many studies acknowledge that product and service characteristics influence digital marketing strategies, most have focused primarily on the effectiveness of specific content types or communication formats. Limited attention has been given to explaining how entrepreneurs evaluate the fit between platform characteristics and business offerings when making platform selection decisions. Consequently, there is a need to understand the alignment between platforms and business offerings as a strategic dimension that influences digital marketing platform selection decisions.

E. Strategic Platform Fit Perspective

The digital marketing literature suggests that the effectiveness of a platform does not depend solely on its popularity, but rather on its suitability to the business context in which it is utilised. Although numerous studies have examined the use of social media, e-commerce, and digital platforms among small and micro-enterprises, most have focused on technology adoption, general platform usage, or the impact of digital platforms on business performance (31), (23), (32). Limited attention has been given to explaining how entrepreneurs strategically select specific platforms, particularly in the context of entrepreneurs operating with limited resources, skills, and organisational capacities, such as asnaf entrepreneurs.

In response to this gap, the present study proposes the Strategic Platform Fit perspective as a conceptual foundation for understanding the digital marketing platform selection

process. This perspective is grounded in the principle of strategic fit, which posits that the effectiveness of a strategy depends on the degree of alignment between organisational resources, market requirements, and the operating environment. Within the context of digital marketing, platform selection is considered effective when there is strategic alignment between platform characteristics, target customers, and the nature of the business offering.

The Strategic Platform Fit perspective comprises three key dimensions. First, Customer Fit refers to the degree of alignment between the characteristics of platform users and a business's target customers. This dimension encompasses factors such as user demographics, customer location, digital media consumption behaviour, and preferences for specific content formats (33), (34). Second, Reach Fit refers to a platform's capability to reach, attract, and generate relevant customers through its reach mechanisms, discoverability features, and algorithmic systems (15), (35), (36). Third, Offering Fit refers to the suitability of a platform for communicating the value of a product or service through communication formats that enable customers to understand, evaluate, and develop confidence in the offering being promoted (37), (38), (34).

Unlike approaches that evaluate platforms in isolation, the Strategic Platform Fit perspective argues that platform selection is the outcome of the simultaneous interaction among these three dimensions. A platform may possess a large user base, yet still be unsuitable if its users do not align with the target customer segment or if the platform is unable to effectively communicate the value of the product or service offered. Therefore, platform effectiveness is not determined solely by platform popularity, but by the degree of strategic alignment between the platform, customers, and business offerings.

Based on the literature review and the research gaps identified, this study proposes the Strategic Platform Fit conceptual framework as a foundation for understanding digital marketing platform selection among asnaf entrepreneurs. The framework suggests that platform selection is shaped by the interaction between customer alignment (Customer Fit), customer reach capability (Reach Fit), and business offering suitability (Offering Fit), as illustrated in Figure 1.

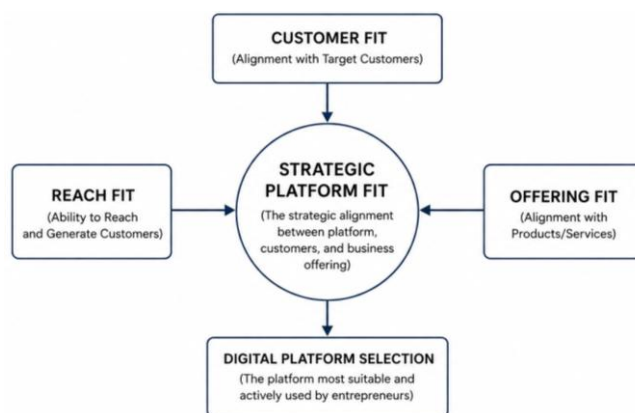


Figure 1. Strategic Platform Fit Conceptual Framework for Digital Marketing Platform Selection.

Figure 1 presents the Strategic Platform Fit conceptual framework proposed in this study. The framework suggests that digital marketing platform selection is not determined by platform popularity alone, but by the degree of strategic alignment among three interrelated dimensions: Customer Fit, Reach Fit, and Offering Fit. Customer Fit refers to the alignment between platform users and target customers, Reach Fit reflects the platform's capability to attract and generate relevant customers, while Offering Fit represents the suitability of the platform for communicating the value of products or services. The interaction among these dimensions shapes the overall Strategic Platform Fit, which subsequently influences digital marketing platform selection among asnaf entrepreneurs.

III. METHODOLOGY

A. Research Design and Study Context

This study employed a qualitative approach using a multiple-case study design to examine the factors influencing digital marketing platform selection among asnaf entrepreneurs. This approach was chosen because digital platform selection is a context-dependent process that involves multiple considerations related to customers, products, costs, operational capabilities, and the digital environment. Accordingly, a qualitative approach enables researchers to gain an in-depth understanding of how asnaf entrepreneurs evaluate and make platform selection decisions based on their experiences and actual business contexts (39), (40).

The study was conducted in Penang, Kedah, and the Federal Territory of Malaysia, as these locations possess active zakat institutions and well-established asnaf entrepreneur development ecosystems. The selection of multiple locations enabled the study to capture variations in institutional support, entrepreneurial experiences, and digital marketing practices among small and micro-enterprises (41). Furthermore, the multiple-case study design allowed the phenomenon under investigation to be examined from diverse perspectives, including those of asnaf entrepreneurs, zakat officers, and digital marketing academics (42).

B. Data Collection and Participant Selection

Data were collected through semi-structured interviews conducted both face-to-face and online. This method was selected because it allows respondents to provide detailed explanations of their experiences and rationales for platform selection while enabling researchers to ask follow-up questions regarding platform usage, marketing challenges, and the forms of support received (43), (44). Each interview lasted approximately 45 to 60 minutes, depending on the respondent's availability and the depth of the discussion.

Participants were selected using purposive sampling based on their direct involvement in, or expertise related to, the phenomenon under investigation. A total of eight respondents participated in the study, comprising three asnaf entrepreneurs, three zakat officers and two academics specialising in digital marketing. Asnaf entrepreneurs were selected because they were directly involved in the use and selection of digital marketing platforms, while zakat officers and academics were included to provide institutional and expert perspectives on digital marketing and asnaf entrepreneur development.

Table 1 Participant Categories

Respondent Category	Code	Number
Asnaf Entrepreneurs	UA1, UA2, UA3	3
Zakat Officers	PZ1, PZ2, PZ3	3
Academics in Digital Marketing	APD1, APD2	2
Total		8

The interview protocol was developed based on the study objectives and the literature on digital marketing, platform selection, and asnaf entrepreneur development. Key areas explored included the types of platforms used, reasons for platform selection, platform suitability for products and services, target customers, promotional costs, digital skills, operational capacity, and the forms of support received. All interviews were conducted in Malay, audio-recorded with participants' consent, and transcribed verbatim for analysis purposes.

In addition to interviews, the study utilised supporting documents and relevant previous studies to enhance understanding of the context of asnaf entrepreneur development and digital marketing practices. The use of these supplementary sources helped support the interpretation of interview data and strengthened understanding of the research phenomenon through source triangulation (45), (41). Data collection was discontinued when the information obtained demonstrated recurring patterns and no longer generated significant new themes, consistent with the principle of data saturation in qualitative research (46), (47).

C. Data Analysis

The data were analysed using thematic analysis to identify patterns, categories, and key themes related to the factors influencing digital marketing platform selection among asnaf entrepreneurs (48). The analytical process began with verbatim transcription and repeated reading of all interview data to gain a comprehensive understanding of the respondents' experiences and contexts. Subsequently, inductive coding was conducted by identifying meaningful units relevant to the research questions. Initial codes sharing similar meanings were then grouped into categories and sub-themes before being refined into broader themes. An inductive approach was employed to allow themes to emerge naturally from the data, while a deductive approach was utilised to connect the findings with relevant literature and theoretical perspectives (49).

Cross-case analysis was also conducted to compare the perspectives of asnaf entrepreneurs, zakat officers, and academics in identifying similarities and differences in platform selection factors (50), (42). To support data management and organisation, generative artificial intelligence applications were used on a limited basis during the preliminary stage of analysis to assist in identifying recurring patterns, suggesting initial codes, and organising descriptive categories. However, all stages of data verification, theme refinement, and final interpretation were undertaken entirely by the researchers to ensure analytical rigour, thematic consistency, and contextual appropriateness of the findings (51), (52). The analysis ultimately generated three major themes explaining the factors influencing digital marketing platform selection among asnaf entrepreneurs.

D. Trustworthiness

The trustworthiness of the findings was enhanced through source triangulation, member checking, and cross-validation of data. Source triangulation was achieved by comparing interview data obtained from asnaf entrepreneurs, zakat officers, and academics with supporting documents and relevant previous studies. The use of multiple sources enabled the phenomenon of digital marketing platform selection to be examined from diverse and complementary perspectives (45), (41).

In addition, continuous cross-validation was conducted between interview data, supporting documents, and relevant literature to ensure the accuracy of the interpretations developed. Member checking was also employed to verify that the researchers' interpretations were consistent with the meanings intended by the participants (53). Direct quotations from participants were included in the findings section to demonstrate a clear connection between the empirical data and the interpretations developed by the researchers.

IV. FINDINGS

The interview findings are presented according to three main themes as follows.

A. Theme 1: Platform Suitability for Target Users

Table 2 Respondents' Excerpts for Theme 1

Respondent Code	Respondent Excerpt
UA2	"A bubble shop is different from other types of businesses. We provide services, so we focus on the local market. Our first outlet was in Kepong, therefore our marketing efforts were specifically targeted at people in Kepong."
UA3	"Facebook is now mostly used by older people. The engagement does not really match my target market. TikTok works because people do not like reading; they prefer watching videos. When they watch a video, they immediately understand what we do. If your target audience is younger people who enjoy video content, then TikTok is suitable. If people prefer reading, then Threads is more appropriate. WhatsApp, on the other hand, is mainly for people in your contact list, meaning those who already know you."
APD2	"The choice of platform does not depend solely on the product, but rather on the users we intend to reach. We need to know where our target users are. If most of them are on TikTok, then TikTok is the appropriate platform. If they are on another platform, then we need to adjust our strategy accordingly."

B. Theme 2: Platform Capability in Reaching and Generating Customers

Table 3 Respondents' Excerpts for Theme 2

Respondent Code	Respondent Excerpt
UA1	"Nowadays, people gather on social media. In the past, we used flyers and distributed them manually, but that is no longer necessary. Social media has become the place where people search for products and services. As long as people view our content and become aware of our business, that is already a positive outcome. Today, it is difficult for a business to grow without using social media."
UA2	"For online marketing, the first thing we focused on was SEO (Search Engine Optimization). We

	optimised our Google Maps profile with customer reviews, client photos, keywords, and hashtags. The first platforms we fully developed were Google Maps, Google Search, and Bing. As a result, whenever people search for a bubble shop, our business appears in the search results. We do not use paid advertisements because there are not many bubble shops within the same area. We then started producing educational videos and customer-focused content. From there, we began converting viewers into customers through video content. Currently, our marketing activities are fully digital and centred on TikTok."
UA3	"When I use Threads, I do not have to actively look for customers. Customers come to me. They post requests asking where they can find services such as massage therapy or cupping treatment. When they click on the recommendations, our business appears immediately. It is almost like a magnet. Many of our customers come from Threads. Although I am not very active on TikTok, I still maintain a presence there so that people know we exist. When they search for us, they can find us. At the very least, it shows that the business is still active and operating."
APD1	"Social media platforms provide extensive reach. With just one engaging video or post, asnaf entrepreneurs can reach a large number of potential customers within a short period of time. In today's digital marketing environment, social media platforms provide opportunities for anyone to attract consumer attention without requiring substantial financial resources. This is particularly important for small businesses and asnaf entrepreneurs who need to acquire customers quickly."
APD2	"In the e-commerce context that I teach, the primary purpose of digital platforms is to reach two types of customers. First, existing customers whom we want to encourage to make repeat purchases. Second, potential customers who have not yet become familiar with our business but whom we want to attract. Reaching potential customers requires greater effort because they are new to the business. Therefore, digital marketing platforms are used to engage both existing and potential customers."
PZ3	"This is why some entrepreneurs are more comfortable using Shopee. Shopee offers greater sales stability. Some entrepreneurs have generated hundreds of thousands in sales through Shopee alone. However, when looking at the broader picture, most asnaf entrepreneurs are not fully engaged in digital platforms. They have yet to effectively integrate conventional and digital marketing approaches."

C. Theme 3: Platform Suitability for the Type and Characteristics of Products or Services

Table 4 Respondents' Excerpts for Theme 3

Respondent Code	Respondent Excerpt
UA1	"I create content based on storytelling. I do not simply promote the product by saying that it tastes good. Instead, I tell a story. For example, why did the customer place the order? What occasion was it for? Who was it intended for? When there is a story behind the product, people can relate to it. I once learned from a content creator who said that simply posting about a delivery or sharing a customer's compliment is not enough. However, if we provide context, such as explaining that the order was made by an employer for staff members who were leaving the company, people can visualise the situation. This encourages them to think, 'If I have a similar event in the future, I could place an order as well.' Every piece of content should have a purpose. Why was the product chosen? Why was the order made? When there is a reason behind the story, people can understand it more easily and become more interested."

UA2	“A bubble shop is different from many other businesses because we provide services. From the beginning, we focused on showing both the process and the results. Even when we started selling products, we applied the same concept. We explain what customers should expect when they purchase our products. With service-based businesses, customers often find it difficult to trust what they cannot see. Once they can see the transformation and the process, they become more confident. For this type of service, video content is much easier to understand than images or written text.”
APD1	“In contemporary digital marketing, authentic content plays a crucial role. Authentic content refers to content that genuinely reflects the reality of the business, whether through product manufacturing processes, preparation methods, usage demonstrations, or actual customer experiences. When entrepreneurs showcase real processes, such as how a product is made or how a service is delivered, customers are more likely to trust the business because they can directly observe the effort and sincerity behind the products or services being offered.”
APD2	“When discussing asnaf entrepreneurs, their products are highly diverse. Some sell freshly prepared food that must be consumed on the same day, while others sell processed food, frozen food, snacks, chilli paste, and products that must be delivered immediately after preparation, such as satay. These categories cannot be marketed using the same approach because the characteristics of the products differ significantly. Content is not merely about the product itself. People do not only look at products; they also respond to stories, emotions, and the reasons why they should make a purchase.”
PZ3	“Most of our entrepreneurs are involved in the food and beverage sector. Approximately 80 percent operate food-related businesses. The remaining entrepreneurs are engaged in activities such as tailoring services, motorcycle workshops, and automotive repair workshops.”

V. DISCUSSION

A. Customer Fit

The findings indicate that digital marketing platform selection among asnaf entrepreneurs is influenced by the degree of alignment between platform characteristics and target customers. Platforms are not selected solely based on popularity or the size of their user base, but rather on their ability to reach customers who are genuinely relevant to the business. As explained by UA2 and UA3, factors such as customer location, user demographics, and platform usage patterns constitute key considerations in determining platform suitability. For asnaf entrepreneurs who operate with limited marketing resources and operational capacity, the ability to precisely reach target customers is considered more important than achieving broad reach that may not translate into actual business outcomes. This finding is consistent with previous studies, which emphasise that the effectiveness of digital marketing depends on the alignment between user characteristics, customer location, and communication strategies (21), (22), (23), (54).

The study also reveals that platform suitability is influenced by the way customers receive and process digital content. According to UA3, TikTok users are generally more attracted to visual content and short-form videos, whereas Threads users tend to prefer text-based content and more detailed explanations. These differences suggest that each platform offers distinct communication formats and user

experiences, which in turn affect its suitability for different products or services. This finding is consistent with previous research demonstrating that the acceptance of digital content is shaped by users' preferences and the communication formats provided by specific platforms (55), (56), (57). This finding suggests that platform selection involves not only identifying where customers are located, but also understanding how they consume and engage with digital content.

Furthermore, the findings indicate that the nature of customer relationships also influences digital marketing platform suitability. UA3 explained that open platforms such as TikTok, Facebook, and Instagram are more appropriate for increasing business visibility and attracting new customers who are unfamiliar with the products or services offered. In contrast, WhatsApp is better suited for maintaining relationships with existing customers through more direct, personal, and responsive communication. This suggests that different platforms perform different functions throughout the customer journey, ranging from business discovery to customer relationship development and retention. Consistent with customer relationship management literature, customer acquisition and customer retention represent complementary but distinct objectives that may require different communication channels and engagement strategies (58)

Taken together, these findings suggest that Customer Fit functions as a strategic filtering mechanism through which entrepreneurs evaluate the suitability of digital marketing platforms. Rather than pursuing maximum exposure or the largest possible audience, entrepreneurs prioritise platforms that provide access to customer segments most likely to generate meaningful business outcomes. This indicates that platform effectiveness is contingent upon the quality of customer alignment rather than the quantity of platform users. From the perspective of Strategic Platform Fit, customer alignment represents a prerequisite for effective platform selection because it determines whether marketing efforts can be directed towards audiences with relevant needs, interests, and purchasing potential. Consequently, Customer Fit constitutes a foundational dimension of Strategic Platform Fit, whereby entrepreneurs evaluate platforms according to the extent to which platform users, communication formats, and relationship-building capabilities align with the intended customer segment. This finding reinforces the argument that digital marketing effectiveness is shaped by the quality of customer-platform alignment rather than by platform popularity alone.

B. Reach Fit

The findings indicate that asnaf entrepreneurs select digital marketing platforms based on their ability to help businesses reach and generate potential customers. Platforms are not evaluated solely on the basis of views, likes, or follower counts, but rather on the extent to which they connect businesses with genuinely relevant customers. As explained by UA1, initial exposure within the digital space is important because it helps ensure that a business remains visible to potential customers before they begin evaluating products or services. This finding is consistent with previous studies highlighting the important role of social media in shaping customer awareness and consideration prior to purchase decisions (59), (60), (15).

The study also reveals that different platforms generate customers through different mechanisms. UA2 explained that the use of Google Maps, combined with keywords, customer reviews, and visual content, increases the likelihood of a business being discovered by customers actively searching for related services. Unlike social media platforms, which expose content to users more broadly, search-based platforms tend to connect businesses with users who already possess specific needs or purchase intentions. This finding is consistent with previous studies demonstrating that discoverability within digital environments influences consumers' propensity to evaluate and select particular businesses (19), (61), (24).

Furthermore, the findings suggest that platform systems play an important role in matching content with potential customers. As observed by UA3, platforms such as Threads are capable of presenting content to users with relevant interests even without the use of paid promotions. This finding supports previous research suggesting that platform systems can identify user interests and distribute content in a more targeted manner (62), (63), (64).

The findings also demonstrate that different platforms perform distinct functions throughout the digital customer journey. APD2 explained that open platforms such as TikTok, Facebook, Instagram, and Threads are more suitable for building awareness and attracting new customers, whereas WhatsApp is more effective for maintaining relationships with existing customers through direct and responsive communication. This finding is consistent with the view that customer acquisition and customer retention constitute fundamental components of customer relationship management (58).

Overall, the findings suggest that a platform's capability to reach and generate customers is not determined solely by market reach or digital visibility. Rather, platform effectiveness depends on its ability to help businesses become discoverable to relevant customers, match content with potential users, and support customer movement across different stages of the digital customer journey.

C. Offering Fit

The findings indicate that digital marketing platform selection is influenced by the type and characteristics of the products or services being offered. Platforms cannot be selected solely on the basis of popularity or habitual usage; rather, they must be aligned with the way customers understand, evaluate, and develop confidence in a particular offering. In this context, products and services have distinct communication requirements because they differ in the extent to which their value can be directly observed by customers.

For food products, the findings reveal that customers do not merely evaluate basic information such as taste, price, or portion size, but also imagine the consumption experience, atmosphere, and satisfaction associated with the product. As explained by UA1, content that simply describes a product as "delicious" is no longer sufficient in a competitive marketplace because it does little to differentiate the product from competing alternatives. Consequently, platforms such as TikTok and Instagram Reels are particularly suitable because they can communicate these experiences through visual content, short-form videos, and engaging storytelling. This finding is consistent with the concept of experience goods, which suggests that customers often rely on

experiential cues when evaluating products prior to consumption (25). It also aligns with research indicating that storytelling can enhance customers' emotional engagement with products and strengthen perceived value (65).

The study also finds that services require a different communication approach from physical products because customers often find it difficult to assess service quality before actual consumption. UA2 explained that customers become more confident when they can observe how the service is delivered and what outcomes they can expect. This finding is consistent with previous studies suggesting that services involve higher levels of uncertainty than physical products (27), (28). The finding is further supported by research demonstrating that visual demonstrations can reduce perceived risk and enhance customer confidence in service offerings (29), (30).

Beyond the nature of the offering itself, the findings indicate that product lifespan also influences the suitability of digital marketing platforms. APD2 explained that products with a short lifespan, such as freshly prepared food intended for same-day consumption, require timely communication because their value diminishes as time passes. This finding is consistent with previous studies suggesting that content visibility duration and product time sensitivity influence customer responses to marketing offers (66), (67), (68), (69).

Overall, the findings demonstrate that digital marketing platform selection should be grounded in the alignment between the characteristics of the business offering and the platform's ability to communicate its value to customers. Experience-oriented products require platforms capable of conveying emotions and usage experiences, whereas services require visual evidence that reduces uncertainty and strengthens customer confidence.

VI. CONCLUSION

This study demonstrates that digital marketing platform selection among asnaf entrepreneurs does not occur uniformly or merely based on platform popularity. Rather, it is shaped through a strategic and contextual decision-making process. The findings reveal that platform selection decisions are influenced by the degree of alignment between target customers, the platform's capability to generate relevant customers, and the platform's suitability in communicating the value of the products or services offered. In this context, the effectiveness of a platform is not determined solely by the size of its user base or its level of visibility, but by the extent to which it can comprehensively fulfil the marketing needs of the business. These findings form the foundation of the Strategic Platform Fit perspective proposed in this study, which explains platform selection as the outcome of the interaction between Customer Fit, Reach Fit, and Offering Fit in optimising digital marketing effectiveness.

From a theoretical perspective, this study contributes to the digital marketing and entrepreneurship literature by introducing the Strategic Platform Fit perspective as a mechanism for explaining the digital marketing platform selection process. Unlike previous studies that have primarily focused on technology adoption, social media usage, or platform effectiveness in general, this study demonstrates that platform selection is a strategic decision-making process involving the interaction between target customers, platform capabilities, and the characteristics of business offerings. Consequently, this study extends the understanding of how

micro-entrepreneurs make marketing decisions within an increasingly diverse and dynamic digital ecosystem.

From a practical perspective, the findings provide important implications for zakat institutions, entrepreneurship development agencies, and entrepreneurship training providers in designing more targeted digital marketing support programmes. Entrepreneurial development initiatives should not focus solely on platform usage or content creation, but should also assist entrepreneurs in evaluating platform suitability based on target customers, customer-generation capabilities, and the nature of the products or services offered. Such an approach has the potential to enhance digital marketing effectiveness, optimise the utilisation of limited resources, and strengthen the competitiveness of asnaf entrepreneurs in the digital marketplace.

Although this study provides a deeper understanding of digital marketing platform selection among asnaf entrepreneurs, several limitations should be acknowledged. The study involved a limited number of respondents and was confined to the context of asnaf entrepreneur development in Malaysia. Therefore, future research may employ larger samples and utilise quantitative or mixed-method approaches to examine the relationships among the dimensions of Customer Fit, Reach Fit, and Offering Fit across more diverse contexts. Furthermore, future studies may explore how factors such as platform algorithms, artificial intelligence, data analytics, and changing consumer behaviour influence the formation of Strategic Platform Fit within an evolving digital marketing environment.

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REFERENCES

- [1] F. Asni, W. Mustafa, K. Ahmad, and N. Subri, "Preliminary Framework For A Digital Marketing Support Scheme For Asnaf Entrepreneurs By Zakat Institutions In Malaysia," *International Journal of Entrepreneurship and Management Practices (IJEMP)*, vol. 8, no. 30, 2025.
- [2] I. A. Jumbri, S. Sharif, and Z. Omar, "Penerimaan E-Dagang dalam Kalangan Usahawan Asnaf di Melaka, Malaysia," *Global Journal Al-Thaqafah*, vol. 13, no. 1, pp. 172-184, 2023.
- [3] M. H. Hasbulah, F. Asni, A. M. Noor, and W. M. A. W. Halim, "Economic impact of Covid-19 outbreak: a study of zakat collection and distribution management in Zakat Penang (ZP)," *International Journal of Academic Research in Business and Social Sciences*, vol. 12, no. 4, pp. 1047-1066, 2022.
- [4] M. Ismail, N. Z. Asyikin Ahmad, and A. Othman, "Overview of Digital Marketing Strategy among Asnaf Entrepreneurs in Malaysia," *International Journal of Academic Research in Business and Social Sciences*, vol. 13, no. 11, pp. 908-917, 2023.
- [5] K. Meerangani, M. Hamid, and M. Jofri, "Empowerment of Majlis Agama Islam Negeri Sembilan's Asnaf Entrepreneurs in The Digital Era," *Journal of Contemporary Islamic Studies*, 2024.
- [6] Department of Statistics Malaysia, "ICT use and access by individuals and households survey report 2024," 2025. [Online]. Available: <https://www.dosm.gov.my>
- [7] T. Meyer, A. Kerkhof, C. Cennamo, and T. Kretschmer, "Competing for attention on digital platforms: The case of news outlets," *Strategic Management Journal*, vol. 45, no. 9, pp. 1731-1790, 2024.
- [8] B. J. Omotosho, "Small scale craft workers and the use of social media platforms for business performance in southwest Nigeria," *Journal of Small Business & Entrepreneurship*, vol. 35, no. 2, pp. 181-196, 2023.
- [9] Y. Al-Qaradawi, *Fiqh al-Zakat: Dirasatu Muqaranah lil Ahkamiha wa Falasafatiha fi zhou'I al-Quran wa al-Sunnah*. Cairo: Maktabah Wahabah, 2003.
- [10] I. A. Jumbri and M. Z. Zainudin, "Pembangunan modal insan dalam kalangan fakir dan miskin sebagai usahawan: kajian kes di Lembaga Zakat Selangor," *Journal of Human Capital Development (JHCD)*, vol. 4, no. 2, pp. 41-56, 2011.
- [11] F. Asni, A. M. Noor, M. H. Hasbulah, M. A. M. Rani, and H. Abd Mutalib, "Analysis Of Maips Strategies In Zakat Management To Address The Impact Of Covid-19 In Perlis," *Journal of Namibian Studies: History Politics Culture*, vol. 35, pp. 1189-1209, 2023.
- [12] S. Sulaiman, N. Abd Hamid, D. O. Rani, S. C. Saruji, and C. M. F. Aimullah, "Determining the success factors of micro-businesses in the post-pandemic era: Empirical evidence from Asnaf entrepreneurship in Malaysia," *Journal of Asian Scientific Research*, vol. 14, no. 1, p. 38, 2024.
- [13] J. I. A. Ismail, A. C. Ahmat, M. N. M. Hussain, and A. B. Hamed, "Cadangan Perancangan Strategik Pemasaran Produk Usahawan Asnaf," *International Journal of Zakat and Islamic Philanthropy*, vol. 1, no. 2, pp. 31-40, 2019.
- [14] K. A. Meerangani, M. F. A. Hamid, S. N. I. Hashim, D. Sharif, M. H. Jofri, and M. S. Mansor, "Digital Platform Potential for Asnaf Zakat Entrepreneurs: A Systematic Literature Review," *International Journal of Academic Research in Business & Social Sciences*, vol. 13, no. 1, 2023.
- [15] G. Appel, L. Grewal, R. Hadi, and A. Stephen, "The future of social media in marketing," *Journal of the Academy of Marketing Science*, vol. 48, pp. 79-95, 2019.
- [16] D. Herhausen, D. Miocevic, R. E. Morgan, and M. H. Kleijnen, "The digital marketing capabilities gap," *Industrial Marketing Management*, vol. 90, pp. 276-290, 2020.
- [17] Y. Su, B. J. Baker, J. P. Doyle, and M. Yan, "Fan engagement in 15 seconds: Athletes' relationship marketing during a pandemic via TikTok," *International Journal of Sport Communication*, vol. 13, no. 3, pp. 436-446, 2020.
- [18] Y. Chen, Q. Wang, J. Xie, and J. Zhang, "The Role of Cross-Border E-commerce Platforms in Digital Economy," 2024. doi: 10.21203/rs.3.rs-5026946/v1.
- [19] M. Nagpal and J. A. Petersen, "Keyword selection strategies in search engine optimization: how relevant is relevance?" *Journal of Retailing*, vol. 97, no. 4, pp. 746-763, 2021.
- [20] R. T. A. Rahim, N. S. M. Noor, M. F. M. Zuki, F. M. N. Azman, and B. N. M. Yusuf, "Hi Tech versus Hi Touch: The Digitalisation of Asnafpreneurs in Perlis," *International Journal of Business and Technopreneurship (IJBT)*, vol. 13, no. 3, pp. 197-208, 2023.
- [21] S. Bernitter, P. Ketelaar, and F. Sotgiu, "Behaviorally targeted location-based mobile marketing," *Journal of the Academy of Marketing Science*, vol. 49, pp. 677-702, 2021. doi: 10.1007/s11747-021-00784-0.
- [22] H. Hussain, T. Alabdullah, E. Ahmed, and K. Jamal, "Implementing Technology for Competitive Advantage in Digital Marketing," *International Journal of Scientific and Management Research*, 2023. doi: 10.37502/ijsmr.2023.6607.
- [23] A. Jha and N. Verma, "Social Media Platforms and User Engagement: A Multi-Platform Study on One-way Firm Sustainability Communication," *Information Systems Frontiers*, vol. 26, pp. 177-194, 2023. doi: 10.1007/s10796-023-10376-8.
- [24] A. A. A. Sharabati, S. Al-Haddad, and R. Hijazi, "Digital marketing and customer purchase intention: The mediating role of customer engagement," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 10, no. 1, p. 100221, 2024.
- [25] P. Nelson, "Information and consumer behavior," *Journal of Political Economy*, vol. 78, no. 2, pp. 311-329, 1970.
- [26] J. Escalas, "Narrative Processing: Building Consumer Connections to Brands," *Journal of Consumer Psychology*, vol. 14, pp. 168-180, 2004.
- [27] V. Mitchell and M. Grotorex, "Risk Perception and Reduction in the Purchase of Consumer Services," *Service Industries Journal*, vol. 13, pp. 179-200, 1993.

- [28] K. Murray and J. Schlacter, "The impact of services versus goods on consumers' assessment of perceived risk and variability," *Journal of the Academy of Marketing Science*, vol. 18, pp. 51-65, 1990.
- [29] M. Zhang, F. Qin, G. Wang, and C. Luo, "The impact of live video streaming on online purchase intention," *The Service Industries Journal*, vol. 40, pp. 656-681, 2020.
- [30] A. Wongkitrungrueng and N. Assarut, "The role of live streaming in building consumer trust and engagement with social commerce sellers," *Journal of Business Research*, vol. 117, pp. 543-556, 2020.
- [31] P. Harrigan, E. Ramsey, and P. Ibbotson, "Entrepreneurial marketing in SMEs: State-of-the-art and future directions," *International Journal of Entrepreneurial Behaviour & Research*, vol. 27, no. 5, pp. 1019-1042, 2021.
- [32] R. Almestarihi, A. Ahmad, R. Frangieh, I. Abu-AlSondos, K. Nser, and A. Ziani, "Measuring the ROI of paid advertising campaigns in digital marketing and its effect on business profitability," *Uncertain Supply Chain Management*, vol. 12, no. 2, pp. 1275-1284, 2024.
- [33] M. J. Pelletier, A. Krallman, F. G. Adams, and T. Hancock, "One size doesn't fit all: a uses and gratifications analysis of social media platforms," *Journal of Research in Interactive Marketing*, vol. 14, no. 2, pp. 269-284, 2020.
- [34] H. Shahbaznezhad, R. Dolan, and M. Rashidirad, "The role of social media content format and platform in users' engagement behavior," *Journal of Interactive Marketing*, vol. 53, no. 1, pp. 47-65, 2021.
- [35] C. Johnson, M. Hills, and L. Dempsey, "An audience studies' contribution to the discoverability and prominence debate," *Convergence*, vol. 30, no. 5, pp. 1625-1645, 2024.
- [36] H. Beyari and T. Hashem, "The role of artificial intelligence in personalizing social media marketing strategies for enhanced customer experience," *Behavioral Sciences*, vol. 15, no. 5, p. 700, 2025.
- [37] H. A. Voorveld, G. Van Noort, D. G. Muntinga, and F. Bronner, "Engagement with social media and social media advertising: The differentiating role of platform type," *Journal of Advertising*, vol. 47, no. 1, pp. 38-54, 2018.
- [38] B. J. Reich and M. Pittman, "An appeal to intimacy: Consumer response to platform-appeal fit on social media," *Journal of Consumer Psychology*, vol. 30, no. 4, pp. 660-670, 2020.
- [39] J. W. Creswell and C. N. Poth, *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, 4th ed. Thousand Oaks, CA: Sage, 2018.
- [40] S. B. Merriam and E. J. Tisdell, *Qualitative Research: A Guide to Design and Implementation*, 4th ed. San Francisco, CA: Jossey-Bass, 2016.
- [41] M. Q. Patton, *Qualitative Research & Evaluation Methods*, 4th ed. Thousand Oaks, CA: Sage, 2015.
- [42] R. K. Yin, *Case Study Research and Applications: Design and Methods*, 6th ed. Thousand Oaks, CA: Sage, 2018.
- [43] S. Brinkmann and S. Kvale, *Interviews: Learning the Craft of Qualitative Research Interviewing*, 3rd ed. Thousand Oaks, CA: Sage, 2015.
- [44] H. Kallio, A. M. Pietila, M. Johnson, and M. Kangasniemi, "Systematic methodological review: developing a framework for a qualitative semi-structured interview guide," *Journal of Advanced Nursing*, vol. 72, no. 12, pp. 2954-2965, 2016.
- [45] N. K. Denzin, *The Research Act: A Theoretical Introduction to Sociological Methods*. New York, NY: McGraw-Hill, 1978.
- [46] G. Guest, A. Bunce, and L. Johnson, "How Many Interviews Are Enough?" *Field Methods*, vol. 18, pp. 59-82, 2006.
- [47] B. Saunders, J. Sim, T. Kingstone, S. Baker, J. Waterfield, B. Bartlam, and C. Jinks, "Saturation in qualitative research: exploring its conceptualization and operationalization," *Quality & Quantity*, vol. 52, no. 4, pp. 1893-1907, 2018.
- [48] V. Braun and V. Clarke, "Using thematic analysis in psychology," *Qualitative Research in Psychology*, vol. 3, no. 2, pp. 77-101, 2006.
- [49] J. Fereday and E. Muir-Cochrane, "Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development," *International Journal of Qualitative Methods*, vol. 5, no. 1, pp. 80-92, 2006.
- [50] M. B. Miles, A. M. Huberman, and J. Saldana, *Qualitative Data Analysis: A Methods Sourcebook*, 3rd ed. Thousand Oaks, CA: Sage, 2014.
- [51] D. L. Morgan, "Exploring the use of artificial intelligence for qualitative data analysis: The case of ChatGPT," *International Journal of Qualitative Methods*, vol. 22, 2023.
- [52] S. De Paoli, "Having a chat with ChatGPT as a qualitative research methodology," *Qualitative Research in Organizations and Management*, vol. 18, no. 4, pp. 395-412, 2023.
- [53] Y. S. Lincoln and E. G. Guba, *Naturalistic Inquiry*. Thousand Oaks, CA: Sage, 1985.
- [54] A. Pandey, P. Mannepal, M. Gupta, R. Dangi, and G. Choudhary, "A Deep Learning-Based Hybrid CNN-LSTM Model for Location-Aware Web Service Recommendation," *Neural Processing Letters*, vol. 56, 2024.
- [55] G. Akobiarek and A. Puyok, "Patterns of Social Media Choice and Use and Their Impacts on Online Political Participation in Sarawak," *Jurnal Komunikasi: Malaysian Journal of Communication*, 2024. doi: 10.17576/jkmjc-2024-4004-01.
- [56] P. Nguyen, "Arousal - Passage To Impulsive Purchase - Exploring The Driving Factors Through TikTok Short Marketing Videos," *EAI Endorsed Transactions on Tourism, Technology and Intelligence*, 2025. doi: 10.4108/eett.10426.
- [57] H. Zhao and C. Wagner, "How TikTok leads users to flow experience: investigating the effects of technology affordances with user experience level and video length as moderators," *Internet Research*, vol. 33, pp. 820-849, 2022.
- [58] A. Payne and P. Frow, "A Strategic Framework for Customer Relationship Management," *Journal of Marketing*, vol. 69, pp. 167-176, 2005.
- [59] X. Lin and X. Wang, "Towards a model of social commerce: improving the effectiveness of e-commerce through leveraging social media tools," *European Journal of Information Systems*, vol. 32, pp. 782-799, 2023.
- [60] C. Leong, A. Loi, and S. Woon, "The influence of social media eWOM information on purchase intention," *Journal of Marketing Analytics*, vol. 10, pp. 145-157, 2021.
- [61] H. J. Tsuei, W. H. Tsai, F. T. Pan, and G. H. Tzeng, "Improving search engine optimization (SEO) by using hybrid modified MCDM models," *Artificial Intelligence Review*, vol. 53, no. 1, pp. 1-16, 2020.
- [62] D. Shah and B. P. S. Murthi, "Marketing in a data-driven digital world: Implications for the role and scope of marketing," *Journal of Business Research*, vol. 125, pp. 772-779, 2021.
- [63] A. Kumar, G. Prakash, and G. Kumar, "Does environmentally responsible purchase intention matter for consumers? A predictive sustainable model developed through an empirical study," *Journal of Retailing and Consumer Services*, vol. 58, p. 102270, 2020.
- [64] G. Prakash, P. K. Singh, A. Ahmad, and G. Kumar, "Trust, convenience and environmental concern in consumer purchase intention for organic food," *Spanish Journal of Marketing-ESIC*, vol. 27, no. 3, pp. 367-388, 2024.
- [65] J. Escalas, "Narrative Processing: Building Consumer Connections to Brands," *Journal of Consumer Psychology*, vol. 14, pp. 168-180, 2004.
- [66] E. Villaespesa and S. Wowkowych, "Ephemeral storytelling with social media: Snapchat and Instagram stories at the Brooklyn Museum," *Social Media + Society*, vol. 6, no. 1, 2020.
- [67] Y. Xu, S. Kapitan, and M. Phillips, "The commercial impact of live streaming: a systematic literature review and future research agenda," *International Journal of Consumer Studies*, vol. 47, no. 6, pp. 2495-2527, 2023.
- [68] H. Goworek, L. Oxborrow, S. Claxton, A. McLaren, T. Cooper, and H. Hill, "Managing sustainability in the fashion business," *Journal of Business Research*, vol. 117, pp. 629-641, 2020.
- [69] J. M. Stenton, V. Kapsali, R. S. Blackburn, and J. A. Houghton, "From clothing rations to fast fashion: Utilising regenerated protein fibres to alleviate pressures on mass production," *Energies*, vol. 14, no. 18, p. 5654, 2021.

Digital Education: The Effects of Artificial Intelligence on the Mathematics and English Achievement of Form Five Asnaf Students in the State of Perlis

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ABSTRACT — This study aimed to evaluate the effectiveness of Artificial Intelligence (AI) in the teaching and learning of Form Five Mathematics and English among students from the asnaf group. The study employed a quasi-experimental design using a mixed-methods approach involving pre-tests and post-tests for both the control and treatment groups. The treatment group received AI-assisted instruction through applications such as ChatGPT, Gemini, Canva AI, and NotebookLM, whereas the control group received conventional classroom instruction. Descriptive analysis was conducted to examine differences in students' achievement before and after the intervention.

The findings revealed that asnaf students in the treatment group demonstrated greater improvements in academic achievement than those in the control group for both Mathematics and English. These findings suggest that AI can enhance students' conceptual understanding, problem-solving skills, and language proficiency through more interactive and personalised learning experiences. The study also found that AI has the potential to reduce educational achievement gaps among asnaf students by supporting self-directed learning and providing immediate feedback. Overall, the study suggests that integrating AI into teaching and learning can improve the quality of education while supporting the development of twenty-first-century learning in schools.

KEYWORDS: Artificial Intelligence (AI); Mathematics; English Language; asnaf students; quasi-experimental; twenty-first-century learning; student achievement.

I. INTRODUCTION

The rapid advancement of Artificial Intelligence (AI) has created new opportunities in education by enabling learning experiences that are more flexible, responsive, and tailored to students' individual needs (UNESCO, 2023). In Malaysia, efforts to strengthen educational technology are aligned with the aspirations of the Malaysia Education Plan 2026-2035, which emphasises the development of a digital education ecosystem to enhance learning quality and reduce

educational disparities (Ministry of Education Malaysia, 2026). Nevertheless, students from the asnaf community continue to face numerous challenges, including limited access to digital learning resources, insufficient academic support outside school, and financial constraints that may negatively affect their academic performance (OECD, 2023). These challenges are particularly evident in Mathematics and English, both of which require continuous practice and consistent instructional support. Consequently, the effective use of digital technology and AI by teachers is considered essential in addressing these learning disparities (UNESCO, 2023; Kasneci *et al.*, 2023). One promising pedagogical approach is the Direct Instruction Method (DIM), a systematic instructional approach that focuses on the gradual mastery of knowledge and skills (Rosenshine, 2012). When combined with AI technologies capable of providing immediate feedback and personalised learning experiences, this approach has considerable potential to enhance learning effectiveness. Therefore, this quasi-experimental study was conducted to examine the effects of AI-supported Direct Instruction Method (DIM) on the Mathematics and English achievement of Form Five SPM candidates from the asnaf group in Perlis.

II. BACKGROUND OF THE STUDY

Mathematics and English achievement are among the key indicators of academic success for secondary school students. However, students from the asnaf community often encounter various challenges that adversely affect their academic performance, including family socioeconomic constraints, limited access to learning resources, inadequate digital devices, and insufficient academic support. These limitations reduce their opportunities to perform at the same level as their peers who have greater access to educational resources. Recent advances in Artificial Intelligence (AI) have created new opportunities for education by providing

more interactive and personalised learning experiences. Applications such as ChatGPT, Gemini, Canva AI, and NotebookLM enable students to understand concepts more effectively, revise lessons, complete assignments, and improve language proficiency through immediate and personalised feedback. Previous studies have reported that well-planned AI integration can enhance students' motivation, engagement, and academic achievement (Kasneci *et al.*, 2023; Tlili *et al.*, 2023). Nevertheless, educational inequality associated with socioeconomic background remains a significant concern. Students from low-income families frequently experience limited access to technology and learning support (OECD, 2023; UNESCO, 2023). Consequently, the integration of AI into Mathematics and English instruction has considerable potential to improve the academic achievement of asnaf students when implemented systematically and supported by appropriate pedagogical approaches.

III. PROBLEM STATEMENT

Various initiatives have been undertaken to expand the use of technology in education. However, the implementation of technology in teaching and learning remains inconsistent across schools and teachers and is often limited to information delivery rather than promoting deeper conceptual understanding (UNESCO, 2023). This challenge is particularly evident among Form Five students from the asnaf community, who have limited access to learning resources and academic support outside school. Such constraints may contribute to persistent learning gaps in Mathematics and English and negatively affect students' performance in the Malaysian Certificate of Education (SPM) examination (OECD, 2023). At the same time, Artificial Intelligence (AI) has gained increasing attention as an educational tool capable of supporting personalised learning experiences, providing immediate feedback, and promoting self-directed learning (Kasneci *et al.*, 2023; Zawacki-Richter *et al.*, 2019). Previous studies have also demonstrated that AI has the potential to improve achievement in Mathematics and English, depending on the instructional design and implementation strategies employed (Kasneci *et al.*, 2023; Tlili *et al.*, 2023).

Despite these promising findings, empirical evidence regarding the use of AI among secondary school asnaf students in Malaysia remains limited. Therefore, this study was conducted to examine the effects of AI on the Mathematics and English achievement of Form Five students from the asnaf community.

A. Research Questions

1. What are the levels of Mathematics and English achievement among Form Five students in the pre-test and post-test for the control and treatment groups?
2. Is there a significant difference in Mathematics and English achievement between students in the control group and those in the treatment group who received AI-assisted instruction?
3. What are students' perceptions of the use of AI as a learning tool for Mathematics and English?

B. Research Hypothesis

H₀₁: There is no significant difference in Mathematics and English achievement between students in the control group and students in the treatment group who received AI-assisted instruction.

IV. METHODOLOGY

This study employed a quasi-experimental research design using a mixed-methods approach. This approach was selected to enable the researchers to evaluate changes in students' academic achievement through quantitative data while simultaneously obtaining a deeper understanding of their learning experiences through qualitative data.

The study involved the administration of pre-tests and post-tests to measure changes in Mathematics and English achievement before and after the AI intervention. Students in the treatment group participated in lessons that integrated AI technologies, whereas students in the control group received conventional instruction without the specific use of AI. The use of this research design enabled comparisons to be made between the two groups in order to determine whether AI integration produced a significant effect on students' academic achievement. In addition, students' feedback was collected to gain insights into their experiences, perceptions, and acceptance of AI in the learning process. The quasi-experimental design was considered appropriate because it allowed the study to be conducted in an authentic school environment without disrupting existing classroom structures. This design is widely adopted in educational research to evaluate the effectiveness of instructional interventions under real classroom conditions.

Previous studies have shown that AI integration in education can enhance student engagement, strengthen self-directed learning, and improve academic achievement through immediate feedback and personalised learning support that matches students' abilities (Kasneci *et al.*, 2023; Tlili *et al.*, 2023). Therefore, this study was conducted to determine the extent to which AI could improve Mathematics and English achievement among Form Five students from the asnaf community. The overall research design is illustrated in Figure 1.

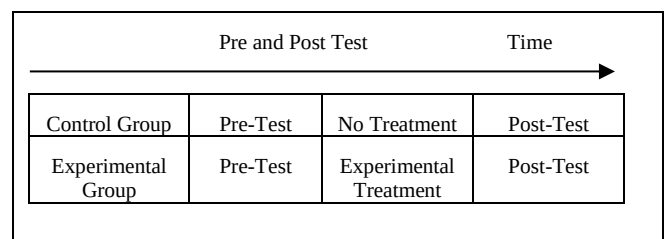


Figure 1. Quasi-experimental design.

Source: Creswell, J. W. (2014). *Educational Research: Planning, Conducting and Evaluating Quantitative and Qualitative Research*. Boston: Pearson College Division.

This study adopted a mixed-methods approach, integrating quantitative and qualitative data to provide a more comprehensive understanding of the phenomenon under investigation. The combination of both approaches enabled the researchers to evaluate the effectiveness of the intervention using academic achievement data while also

gaining deeper insights into students' learning experiences and perceptions of AI-supported learning. Qualitative data obtained through semi-structured interviews were used to complement and explain the quantitative findings derived from the pre-test and post-test results. This approach also facilitated data triangulation, thereby enhancing the credibility and trustworthiness of the research findings (Creswell, 2018).

A. Research Sample

This quasi-experimental study involved 100 Form Five students who were candidates for the Malaysian Certificate of Education (SPM) from the asnaf community across five secondary schools in the state of Perlis. The research sample was equally divided into two groups: 50 students in the treatment group and 50 students in the control group. The treatment group participated in instructional sessions using the Direct Instruction Method (DIM) integrated with Artificial Intelligence (AI). During the intervention, teachers utilised AI applications such as ChatGPT, Gemini, NotebookLM, and Canva AI to develop more interactive learning materials, generate differentiated practice activities tailored to students' ability levels, and provide real-time instructional support. Students were also guided in using these AI applications to improve their understanding of Mathematical concepts, solve problems, and enhance their English language proficiency.

In contrast, the control group received instruction using the Direct Instruction Method (DIM) without AI integration. Teaching was conducted using conventional instructional resources, including textbooks, learning modules, and drill-and-practice exercises commonly employed in schools. Both groups received the same instructional content; however, the treatment group differed in that AI technologies were integrated into the teaching and learning process.

B. Research Instruments

i) Reliability

The research instrument consisted of one Mathematics test and one English Language test, both of which were administered as the pre-test and post-test. Each instrument comprised 20 multiple-choice items and 10 structured-response items, with a total score of 100 marks. To ensure the reliability of the instruments, a pilot study was conducted involving 30 students who were not included in the actual research sample. The analysis yielded a KR-20 reliability coefficient of 0.89, indicating a high level of internal consistency and confirming that the instruments were suitable for use in the study. The test items were developed based on Bloom's Revised Taxonomy, encompassing the six cognitive levels of remembering, understanding, applying, analysing, evaluating, and creating (Anderson & Krathwohl, 2001). The scoring scheme followed the format of the current public examination, with 40% of the total marks allocated to the multiple-choice items and 60% allocated to the structured-response items. Students' achievement was interpreted according to the mastery levels established by the Ministry of Education Malaysia (Ministry of Education Malaysia, 2018).

ii) Face and Content Validity

Face and content validity were established to ensure that each test item accurately measured the intended constructs while remaining aligned with the prescribed curriculum content. The validation process involved one officer from the Perlis State Education Department and three expert teachers with extensive experience in teaching Mathematics and English Language at the secondary school level. The panel of experts evaluated each test item in terms of language clarity, content accuracy, level of difficulty, and alignment with the Curriculum and Assessment Standard Document (DSKP). This evaluation was conducted to ensure that every item appropriately measured the intended learning outcomes while adequately representing the relevant cognitive levels of Bloom's Revised Taxonomy and the requirements of the current national curriculum (Ary *et al.*, 2010; Ministry of Education Malaysia, 2018).

iii) AI-Assisted Direct Instruction Method (DIM)

The intervention for the treatment group was implemented using the Direct Instruction Method (DIM) integrated with Artificial Intelligence (AI) in the teaching of Form Five Mathematics and English. In Mathematics, AI was used to explain complex concepts, provide step-by-step guidance for problem-solving, generate practice exercises tailored to students' ability levels, and deliver immediate feedback. In English Language, AI supported the development of students' writing skills, grammar, vocabulary, and reading comprehension through interactive learning activities.

Before the intervention commenced, the participating teachers received training on the effective use of AI in teaching and learning. During each instructional session, teachers first introduced the key concepts before students engaged in individual or collaborative learning activities using the designated AI applications. Students used AI to obtain additional explanations, explore concepts in greater depth, and complete learning tasks, while teachers guided them in the ethical use of AI and assisted them in evaluating the accuracy and reliability of AI-generated information. All completed learning tasks were uploaded to the Padlet platform for sharing, discussion, and reflection. The intervention was implemented over four weeks, comprising three main instructional sessions, with a total instructional duration of three hours for each subject.

iv) Conventional Direct Instruction Method (DIM) without AI

The control group received instruction using the Direct Instruction Method (DIM) without the integration of Artificial Intelligence (AI). Teaching was conducted using conventional instructional practices commonly implemented in schools, supported by existing learning resources such as textbooks, learning modules, worksheets, and written exercises. During each instructional session, teachers systematically explained the lesson content before students completed reinforcement activities using the prepared exercises. Throughout the teaching and learning process, students were given opportunities to ask questions and receive direct guidance from their teachers. The duration of the intervention for the control group was identical to that of the treatment group to ensure that any differences in

learning outcomes could be attributed to the use of AI rather than variations in instructional time or curriculum content. All instructional sessions were conducted in accordance with the Form Five Curriculum and Assessment Standard Document (DSKP).

C. Data Collection Procedure

Data collection commenced with discussions between the researchers and the participating schools to coordinate the research schedule without disrupting the normal teaching and learning process. During the first week, all participants sat for the pre-test to determine their initial achievement levels in Mathematics and English Language. The intervention was subsequently implemented over a period of four weeks, beginning in Week Two and continuing until Week Five. The post-test was administered in Week Six to assess changes in students' achievement following the intervention. The interval between the pre-test and post-test was one month, which is consistent with the recommendations for quasi-experimental research in educational studies (Creswell, 2018). In addition to the quantitative data, semi-structured interviews were conducted with several students from the treatment group to obtain more in-depth information regarding their learning experiences, perceptions, and acceptance of the use of Artificial Intelligence (AI) in the learning of Mathematics and English Language.

D. Data Analysis

Quantitative data were analysed using IBM SPSS through both descriptive and inferential statistical analyses. Descriptive statistics, including frequency, percentage, mean, and standard deviation, were used to describe students' achievement in the pre-test and post-test.

A paired-samples t-test was employed to examine changes in students' achievement within the same group, while an independent-samples t-test was used to determine differences in achievement between the treatment group and the control group. Interview data were analysed using thematic analysis through the processes of coding, theme categorisation, and data interpretation. The integration of quantitative and qualitative findings enabled a more comprehensive evaluation of the effectiveness of AI in improving the Mathematics and English achievement of Form Five students from the asnaf community.

The research findings were presented in the form of tables, graphs, and narrative descriptions to facilitate interpretation and comparison between the two research groups. The interpretation of students' achievement was based on the following performance categories:

- | | | |
|-------|------------|-----------|
| (i) | 80% - 100% | Excellent |
| (ii) | 60% - 79% | Good |
| (iii) | 30% - 59% | Moderate |
| (iv) | 0% - 39% | Poor |

All interview sessions were audio-recorded with the participants' consent and transcribed verbatim by the researchers. The completed transcripts were cross-checked against the original audio recordings to ensure the accuracy of the data. The qualitative data were analysed using the thematic analysis approach proposed by Boyatzis (1998).

The analysis involved repeated reading of the interview transcripts, coding the data, grouping categories with similar meanings, and generating the main themes.

The analysis identified several major themes relating to students' experiences of using AI in learning Mathematics and English Language. These themes included increased interest and motivation to learn, easy access to explanations and immediate feedback, greater confidence in completing learning tasks, and opportunities to explore new approaches to learning. Students also reported that AI helped them understand difficult concepts more clearly, particularly in Mathematics problem-solving and English language learning. These interview findings provided a deeper understanding of students' learning experiences and complemented the quantitative findings. Overall, the qualitative findings were organised according to the identified themes to enable a systematic interpretation of students' perceptions of the use of AI in teaching and learning.

V. FINDINGS

This study involved 100 Form Five students from the asnaf community selected from five secondary schools in the state of Perlis. Of the total participants, 50 students were assigned to the treatment group, which received instruction through the AI-assisted Direct Instruction Method (DIM), while the remaining 50 students were assigned to the control group, which received instruction using the conventional Direct Instruction Method (DIM) without AI support. Data analysis was conducted to address all the research questions and test the proposed hypothesis. Descriptive statistics were employed to describe the participants' profiles and compare students' achievement based on their pre-test and post-test scores in both groups. The statistical measures included frequency, percentage, mean, and standard deviation.

To determine the effectiveness of the intervention on students' Mathematics and English achievement, Analysis of Covariance (ANCOVA) was performed using pre-test scores as the covariate. The use of ANCOVA controlled for initial differences between the two groups before comparing post-test performance. Consequently, any differences observed after the intervention could be interpreted more accurately as the effect of AI integration in teaching and learning.

The findings are presented according to the research questions. Quantitative and qualitative findings are reported separately before being integrated in the discussion to provide a comprehensive understanding of the effectiveness of AI in improving Mathematics and English achievement among Form Five students from the asnaf community.

A. Comparison of Mathematics and English Achievement

Table 1 presents the mean scores, standard deviations, and gain scores for both the treatment and control groups.

Table 1. Descriptive Statistics of Mathematics And English Achievement

Subject	Group	Pre-Test M (SD)	Post-Test M (SD)	Gain Score
Mathematics	Treatment	48.92 (15.30)	56.90 (14.81)	+7.98
	Control	26.74 (9.80)	30.84 (9.50)	+4.10
English Language	Treatment	64.42 (10.62)	72.78 (9.89)	+8.36
	Control	55.14 (13.13)	60.66 (13.23)	+5.52

The pre-test and post-test analyses indicated that both groups demonstrated improvements in academic achievement following the intervention. However, the improvement observed in the treatment group was consistently greater than that of the control group in both subjects. For Mathematics, the treatment group achieved a gain score of 7.98 points, compared with 4.10 points for the control group. Similarly, in English, the treatment group improved by 8.36 points, whereas the control group recorded an improvement of 5.52 points. These findings suggest that the AI-assisted Direct Instruction Method (DIM) has greater potential to enhance students' academic achievement than conventional instruction without AI. Although both instructional approaches contributed to improved student performance, the larger gains achieved by the treatment group indicate that AI integration provided additional value to the teaching and learning process. The statistical significance of these differences was subsequently examined using Analysis of Covariance (ANCOVA).

B. Effectiveness of the Intervention Based on ANCOVA

ANCOVA was conducted to determine the effect of the intervention after controlling students' pre-test scores. The results are presented in Table 2.

Table 2 Ancova Results and Intervention Effect Size

Subject	F(1,97)	p	Adjusted Mean (Treatment)	Adjusted Mean (Control)	η^2p
Mathematics	28.03	<0.001	46.75	40.99	0.224
English Language	14.41	<0.001	68.61	64.83	0.129

The ANCOVA results revealed a statistically significant difference between the treatment and control groups for both Mathematics, $F(1,97) = 28.03$, $p < .001$, and English, $F(1,97) = 14.41$, $p < .001$. After controlling for pre-test scores, the treatment group achieved significantly higher adjusted mean scores than the control group in both subjects.

The effect size analysis indicated that the intervention produced a large effect on Mathematics achievement (partial $\eta^2 = 0.224$) and a moderate effect on English achievement (partial $\eta^2 = 0.129$). These findings demonstrate that the AI-assisted Direct Instruction Method (DIM) significantly improved the Mathematics and English achievement of Form Five students from the asnaf community.

C. Students' Perceptions of the Use of AI in Learning

In gaining a deeper understanding of students' experiences in using Artificial Intelligence (AI) for learning Mathematics and English Language, semi-structured interviews were conducted with ten students from the treatment group who were randomly selected. Each interview lasted approximately 15 to 20 minutes and was conducted in Malay. All interview sessions were audio-recorded, transcribed verbatim, and reviewed to ensure the accuracy of the data. The interview data were analysed using thematic analysis, involving the processes of transcript familiarisation, data coding, category development, and theme generation. The analysis identified three major themes that were consistently reported by the participants: more engaging and enjoyable learning experiences, increased motivation to learn, and new learning experiences through the use of AI in the learning process.

Theme 1: More Engaging and Enjoyable Learning Experiences

Many students reported that the use of AI made the learning sessions more engaging compared to the conventional teaching methods they had previously experienced. Direct interaction with AI applications enabled them to explore the learning content more actively rather than relying solely on teachers' explanations. One student explained:

"I gained a new learning experience through this approach. Learning became more enjoyable and made me more interested in studying Mathematics and English. My teacher also provided additional explanations that helped me understand the topics better." (M3)

Theme 2: Increased Motivation and Student Engagement

The analysis also revealed that the use of AI enhanced students' motivation to participate actively in the learning process. Students felt more confident in completing learning tasks because they received additional guidance and immediate feedback throughout the learning activities. This was illustrated by one participant as follows:

"This learning approach is enjoyable because I can complete my assignments at home and receive feedback from my teacher. I can also see how my classmates complete their tasks and use them as references." (M6)

These findings indicate that the use of AI not only supports self-directed learning but also encourages interaction and knowledge sharing among students.

Theme 3: New Learning Experiences and the Development of Digital Skills

Most students perceived the use of AI as a new and challenging learning experience. They needed to learn how to interact effectively with AI applications in order to obtain the information or solutions they required. One student stated:

"At first, I found it quite difficult because I had to learn how to give appropriate prompts to the AI. However, over time, I began to enjoy using it. I gained a new learning experience and became more interested in learning. I could also share my work with my classmates through the platform used in class." (M8)

These findings suggest that the use of AI not only enhances students' academic learning but also supports the development of digital competencies that are increasingly essential in today's educational environment. Overall, the interview findings indicate that students responded positively to the use of AI and viewed the technology as a valuable learning support that helped them understand lesson content more effectively. The integration of the Direct Instruction Method (DIM) with AI also created a learning environment that was more interactive, meaningful, and student-centred.

VI. DISCUSSION

The findings of this study indicate that the AI-assisted Direct Instruction Method (DIM) significantly improved the Mathematics and English Language achievement of Form Five students from the asnaf community. The pre-test results showed that there were no significant differences between the treatment group and the control group before the intervention, indicating that both groups had comparable levels of academic achievement at the outset of the study. However, following the intervention, the treatment group demonstrated substantially greater improvement than the control group in both Mathematics and English Language. These findings suggest that the integration of Artificial Intelligence (AI) into the Direct Instruction Method (DIM) enhanced students' learning by providing immediate feedback, personalised explanations, and learning activities tailored to individual learning needs. In Mathematics, AI supported students in understanding concepts more effectively and improved their problem-solving skills. In English Language, AI facilitated the development of writing skills, grammar, vocabulary, and reading comprehension through interactive learning experiences.

The findings are consistent with previous studies conducted by Kasneci et al. (2023), Tlili et al. (2023), and Zawacki-Richter et al. (2019), which reported that the integration of AI in education can improve students' academic achievement, increase learning engagement, and promote self-directed learning. The interview findings further revealed that students responded positively to the use of AI in teaching and learning. They perceived AI-assisted learning as more engaging, interactive, enjoyable, and easier to understand than conventional classroom instruction. Students also reported that AI increased their motivation to learn, enhanced their confidence in completing learning tasks, and provided meaningful opportunities to develop digital literacy skills. Nevertheless, several challenges were identified during the implementation of the intervention, including variations in students' digital literacy skills, teachers' readiness to integrate AI effectively into classroom instruction, and limitations related to Internet connectivity and technological infrastructure.

Therefore, the successful implementation of AI in education requires:

- continuous professional development and training for teachers;
- adequate technological infrastructure in schools;
- reliable Internet connectivity to support AI-assisted learning; and

- clear implementation guidelines and policies to ensure that AI is used ethically and effectively as a tool to support, rather than replace, quality teaching and learning.

These findings demonstrate that the integration of the AI-assisted Direct Instruction Method (DIM) has considerable potential to improve students' academic achievement while fostering a more engaging, personalised, and student-centred learning environment.

VII. CONCLUSION

This study examined the effectiveness of the AI-assisted Direct Instruction Method (DIM) in improving the Mathematics and English Language achievement of Form Five students from the asnaf community in Perlis. The findings showed that students in the treatment group achieved significantly higher improvements than those in the control group in both subjects following the intervention. The Analysis of Covariance (ANCOVA) further confirmed that the differences in post-test achievement remained statistically significant after controlling for students' pre-test scores, indicating that the integration of Artificial Intelligence (AI) had a positive effect on students' academic achievement. The qualitative findings also supported the quantitative results. Students reported that AI-assisted learning increased their interest, motivation, and engagement in learning. They further indicated that AI helped them understand lesson content more effectively while making the learning process more interactive, meaningful, and enjoyable. Overall, the findings suggest that integrating the Direct Instruction Method (DIM) with Artificial Intelligence (AI) has considerable potential to enhance the academic achievement of students from the asnaf community. However, the successful implementation of AI in teaching and learning depends on several key factors, including continuous professional development for teachers, strong digital literacy among both teachers and students, and adequate technological infrastructure with reliable Internet access. When these conditions are fulfilled, AI can serve as an effective pedagogical tool that enhances the quality of teaching and learning while supporting more equitable and inclusive educational opportunities.

REFERENCES

- [1] Anderson, L. W., & Krathwohl, D. R. (2001). A taxonomy for learning, teaching and assessing: A revision of Bloom's taxonomy of educational objectives. New York: Longman.
- [2] Ary, D., Jacobs, L. C., Sorensen, C., & Razavieh, A. (2010). Introduction to research in education (8th ed.). Belmont, CA: Wadsworth.
- [3] Boyatzis, R. E. (1998). Transforming qualitative information: Thematic analysis and code development. Thousand Oaks, CA: Sage Publications.
- [4] Chassignol, M., Khoroshavin, A., Klimova, A., & Bilyatdinova, A. (2018). Artificial intelligence trends in education: A narrative overview. *Procedia Computer Science*, 136, 16–24. <https://doi.org/10.1016/j.procs.2018.08.233>
- [5] Clark, R. C., & Mayer, R. E. (2023). E-learning and the science of instruction: Proven guidelines for consumers and designers of multimedia learning (5th ed.). Hoboken, NJ: Wiley.
- [6] Creswell, J. W., & Creswell, J. D. (2018). Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.). Thousand Oaks, CA: Sage Publications.
- [7] Field, A. (2018). Discovering statistics using IBM SPSS statistics (5th ed.). Thousand Oaks, CA: Sage Publications.

- [8] Kasneci, E., Sessler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., Gasser, U., Groh, G., Günnemann, S., Hüllermeier, E., Krusche, S., Kutyniok, G., Michaeli, T., Nerdel, C., Pfeiffer, F., Poquet, O., Sailer, M., Schmidt, A., Seidel, T., ... Kasneci, G. (2023). ChatGPT for good? On opportunities and challenges of large language models for education. *Learning and Individual Differences*, 103, 102274. <https://doi.org/10.1016/j.lindif.2023.102274>
- [9] Kementerian Pendidikan Malaysia. (2018). *Dokumen Standard Kurikulum dan Pentaksiran Bahasa Inggeris Tingkatan 5*. Putrajaya: Bahagian Pembangunan Kurikulum, Kementerian Pendidikan Malaysia.
- [10] Kementerian Pendidikan Malaysia. (2018). *Dokumen Standard Kurikulum dan Pentaksiran Matematik Tingkatan 5*. Putrajaya: Bahagian Pembangunan Kurikulum, Kementerian Pendidikan Malaysia.
- [11] OECD. (2023). PISA 2022 results (Volume I): The state of learning and equity in education. Paris: OECD Publishing.
- [12] Rosenshine, B. (2012). Principles of instruction: Research-based strategies that all teachers should know. *American Educator*, 36(1), 12–19.
- [13] Tlili, A., Shehata, B., Adarkwah, M. A., Bozkurt, A., Hickey, D. T., Huang, R., & Agyemang, B. (2023). What if the devil is my guardian angel? ChatGPT as a case study of using chatbots in education. *Smart Learning Environments*, 10(15), 1–24. <https://doi.org/10.1186/s40561-023-00237-x>
- [14] UNESCO. (2023). Guidance for generative AI in education and research. Paris: UNESCO.
- [15] Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education—Where are the educators? *International Journal of Educational Technology in Higher Education*, 16(39), 1–27. <https://doi.org/10.1186/s41239-019-0171-0>

REPROEDU-PLATFORM: Development and Evaluation Design of an Interactive Digital Education Platform to Improve Reproductive Health Knowledge among University Students

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ABSTRACT — Reproductive health literacy among university students remains a major public health concern worldwide. Although digital technology has significantly transformed access to health information, many students continue to experience misinformation, limited access to professional counseling, and insufficient reproductive health knowledge. Digital-based educational interventions have emerged as promising strategies to address these challenges. This study proposes the development and evaluation framework of REPROEDU-PLATFORM, an interactive digital reproductive health education platform designed specifically for university students. The platform integrates branching storytelling, anonymous consultation services, and evidence-based educational materials validated by reproductive health experts. The study adopts a quasi-experimental non-equivalent control group post-test-only design. Students in the intervention group received education through REPROEDU-PLATFORM, while those in the control group received conventional PDF-based educational materials. The primary outcome is reproductive health knowledge measured using a validated questionnaire. Secondary outcomes include user engagement, learning satisfaction, and platform usability. This study provides a robust scientific foundation for implementing innovative digital reproductive health education and contributes to improving reproductive health literacy among university students.

KEYWORDS: Reproductive health, digital education, university students, mobile health, health promotion.

I. INTRODUCTION

Reproductive health represents a vital component in developing the overall quality of human resources [2]. The World Health Organization (WHO) defines reproductive health as a state of physical, mental, and social well-being

relating to the reproductive system, its functions, and its biological processes [2]. University students, as young adults, reside in a critical transitional phase that is highly vulnerable to various reproductive health dilemmas [3]. These problems include a high prevalence of sexually transmitted infections, risky sexual behaviors, unintended pregnancies, and underutilized professional reproductive healthcare services [6].

The rapid advancement of digital technology has fundamentally transformed how young populations acquire health literacy [1]. Empirical data indicates that a vast majority of university students rely heavily on the internet and social media networks as their primary sources for health-related info [9]. However, the quality of digital content available on public domains is frequently inaccurate, highly unvetted, and lacks a solid foundation in rigorous empirical science [5]. Relying on such invalid digital information can perpetuate severe misconceptions and significantly escalate the risks of improper healthcare decision-making among students [6].

Prior investigations demonstrate that digital-based health education can effectively optimize access, expand structural learning flexibility, and improve user immersion [7]. Nevertheless, a vast majority of available digital reproductive health interventions remain largely passive, non-immersive, and lack real-time pedagogical interaction [4]. Furthermore, many university students express intense hesitation to address reproductive issues or seek professional advice due to deeply rooted social stigmas, embarrassment, and concerns over personal privacy breach [8]. Therefore, a pressing imperative exists to design a digital learning

infrastructure that can deliver active engagement while safeguarding user anonymity [10]. The REPROEDU-PLATFORM was explicitly developed to address this gap by integrating branching storytelling simulations, an anonymous encrypted consultation module, and evidence-based clinical materials [1]. Consequently, the objective of this study is to empirically develop and evaluate the short-term efficacy of the REPROEDU-PLATFORM in optimizing reproductive health knowledge among university students compared to conventional digital material approaches [5].

II. RESEARCH GAP AND NOVELTY

Although previous academic works have explored various digital modalities for reproductive health education—including traditional e-learning packages, educational videos, generic mobile apps, and public health portals—they exhibit several core operational constraints [5]. First, the instructional content delivery remains strictly passive, one-way, and non-immersive [4]. Second, existing systems do not provide simulated clinical case management or active decision-making processes for young users [7]. Third, they fail to supply a thoroughly anonymous, safe portal for peer-to-peer or professional consultation [8]. Fourth, user retention and behavioral engagement indices are rarely evaluated or sustained [6]. Lastly, prior systems do not holistically unify validated education and secure clinical counseling within a single, unified digital touchpoint [10].

To transcend these baseline limitations, the structural novelty of this study lies in:

1. The utilization of interactive *Branching Storytelling* simulations as a primary cognitive-active learning architecture [7].
2. The implementation of an encrypted *Anonymous Consultation System* designed explicitly to bypass deep-seated psychological barriers among university students [8].
3. The seamless structural integration of expert-validated health education and professional healthcare clinical advice within a singular, centralized digital ecosystem [1].
4. The deployment of an evidence-based repository meticulously peer-reviewed and validated by independent reproductive health experts [2].
5. The utilization of a rigorous quasi-experimental experimental framework to evaluate short-term educational gains [5].

III. THEORETICAL FRAMEWORK

The programmatic architecture and behavioral mechanics of the REPROEDU-PLATFORM are strictly anchored upon two foundational behavioral models: the Health Belief Model (HBM) and the Social Cognitive Theory (SCT) [7].

A. Health Belief Model (HBM)

The HBM dictates that an individual's drive to engage in preventive health actions is governed by five essential structural perceptions [6]. These comprise *perceived susceptibility* to health threats, *perceived severity* of complications, *perceived benefits* of preventive actions, *perceived barriers* to lifestyle modifications, and individual *self-efficacy* [5]. Within the platform, the *Anonymous Consultation System* is designed to drastically lower *perceived barriers* (social shame/stigma), while the expert-validated modules heighten *perceived benefits* and *self-efficacy* regarding reproductive literacy [8].

B. Social Cognitive Theory (SCT)

The SCT asserts that behavioral modification and knowledge assimilation proceed through a dynamic triadic reciprocity encompassing *observational learning*, *enactive learning* (direct experiential practice), *social interaction*, and *behavioral reinforcement* [7]. The REPROEDU-PLATFORM operationalizes these tenets by using *Branching Storytelling*, allowing students to undergo direct enactive simulation where their simulated actions lead to immediate pedagogical feedback and cognitive reinforcement [4]. The conceptual synergy of these two complementary models establishes a potent framework to safely maximize student health literacy [10].

IV. CONCEPTUAL FRAMEWORK

The conceptual framework of this study illustrates the operational pathways through which the digital intervention optimizes behavioral and cognitive outcomes among university students. The structural relationships between the independent, mediating, and dependent variables are defined as follows:

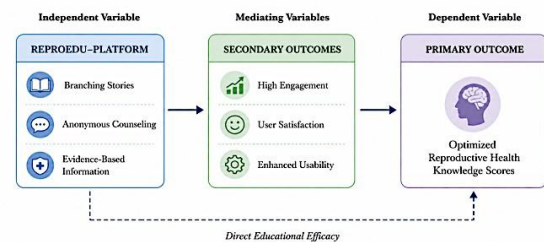


Figure 1. Conceptual framework of REOROEDU-PLATFORM and Its impact on Reproductive Health Knowledge.

V. PLATFORM ARCHITECTURE

The functional backend of the REPROEDU-PLATFORM is structured into three integrated core components:

A. Branching Storytelling Module

This module places the student inside a safe, simulation-based case narrative concerning reproductive health dilemmas [7]. As students choose specific behavioral courses of action, the software branches into distinct logical pathways, delivering real-time educational consequences and clinical feedback [4].

B. Anonymous Consultation System

This secure sub-system permits students to communicate anonymously with certified healthcare professionals [8]. All chat matrices, queries, and data logs undergo point-to-point encryption to protect user identity and maintain extreme confidentiality [10].

C. Evidence-Based Learning Materials

The platform maintains a curated database validated by external medical panels [2]. The content repository encompasses:

- Reproductive anatomy and human physiology [2].
- Sexual health, family planning, and modern contraception [3].
- Pathophysiology and prevention of sexually transmitted infections (STIs) [6].
- Reproductive human rights and the systematic prevention of sexual violence [4].

VI. METHODS

A. Study Design

This study utilized a quantitative *Quasi-Experimental Non-Equivalent Control Group Post-Test Only Design* to measure the immediate impact of the platform [5].

B. Population and Sample

The target population comprised active university students enrolled at the institution [5]. Utilizing a strict *Purposive Sampling* methodology, a total sample size of 300 active students was successfully recruited and analyzed [6].

C. Eligibility Criteria

The inclusion criteria required participants to be between 18–24 years of age, actively enrolled as undergraduate students, possess reliable internet connectivity, and provide written informed consent [5], [9]. The exclusion criteria barred any student who had undergone formal reproductive health training within the preceding 6 months or those who failed to complete the assigned platform modules [6].

D. Research Groups

The sample was divided equally into two distinct parallel tracks:

- Intervention Group (n=150):** Received exclusive educational exposure through the interactive modules of the REPROEDU-PLATFORM [1].
- Control Group (n=150):** Received the exact identical educational content delivered via conventional, static digital PDF documentation [5].

E. Instrument and Data Analysis

The primary data gathering tool was a validated reproductive health knowledge questionnaire containing multiple-choice items covering all core topics, which underwent exhaustive internal validity and reliability testing ($r > 0.361$; Cronbach's $\alpha = 0.82$) [5]. Continuous variables were compiled as Mean $\pm$ Standard Deviation (SD) [6]. Inferential statistical hypothesis testing was executed via an *Independent Samples*

t-Test utilizing SPSS software, with the statistical significance threshold strictly set at $\alpha = 0.05$ [7].

VII. OPERATIONAL VARIABLES

The core operational definitions, measurements, and metrics utilized throughout the trial are structured in the following table:

Variable	Operational Definition	Measurement Instrument	Data Scale
REPROEDU-PLATFORM	Exposure to the interactive digital education platform vs. static materials [1].	Digital Application Analytics Logging System [7].	Nominal (Intervention vs. Control)
Reproductive Health Knowledge	The post-test score attained by the respondent reflecting factual comprehension [5].	Validated Expert-Reviewed Knowledge Questionnaire [6].	Interval (Continuous Score metrics)

VIII. RESULTS AND DISCUSSION

A. Demographic Characteristics of Respondents

The baseline demographic characteristics of the 300 active university students who completed the post-test evaluation are meticulously summarized in Table 1 [5].

Table 1 Demographic Characteristics of Respondents (N=300)

Characteristic	Intervention Group (n=150)	Control Group (n=150)	Total (N=300)
Age (Years)			
* 18–20	85 (56.7%)	82 (54.7%)	167 (55.7%)
* 21–24	65 (43.3%)	68 (45.3%)	133 (44.3%)
Gender			
* Male	60 (40.0%)	62 (41.3%)	122 (40.7%)
* Female	90 (60.0%)	88 (58.7%)	178 (59.3%)
Academic Year			
* First / Second Year	95 (63.3%)	92 (61.3%)	187 (62.3%)
* Third / Fourth Year	55 (36.7%)	58 (38.7%)	113 (37.7%)

As demonstrated in Table 1, the vast majority of the respondents fell within the 18–20 age bracket (55.7%) and identified as female (59.3%) [2]. The distribution of baseline demographic variables between the intervention cohort and the parallel control cohort exhibited a highly homogeneous pattern, thereby validating the post-intervention comparative analysis [3].

B. Efficacy Analysis of REPROEDU-PLATFORM on Knowledge

The Independent Samples t-Test was deployed to test the primary research hypothesis by contrasting the continuous post-test knowledge scores achieved by both student arms [5]. The final statistical output is presented in Table 2 [6].

Table 2 Post-Intervention Differences in Reproductive Health Knowledge Scores Between Groups

Variable	Intervention Group (REPROEDU- PLATFORM) (n=150)	Control Group (PDF Material) (n=150)	t-value	p-value ($\alpha=0.05$)
Reproductive Health Knowledge Score	81.20±9.15	73.40±10.22	7.025	< 0.001*

* Significant at $p<0.05$ Values are expressed as Mean $\pm$ Standard Deviation (SD).

The Independent Samples t-Test results compiled in Table 2 demonstrate a statistically profound difference in educational outcomes between the two arms ($t=7.025$; $p<0.001$) [7]. Since the computed p -value resides far below the pre-established alpha significance threshold of 0.05, the null hypothesis is rejected [6]. This provides robust, unbiased empirical proof that the cohort utilizing the interactive REPROEDU-PLATFORM attained significantly superior reproductive health knowledge scores compared to the control peers exposed to conventional PDF texts [10].

C. Analysis of Secondary Platform Outcomes

The secondary multi-dimensional outcomes were captured exclusively from the intervention arm to determine system feasibility, user engagement, satisfaction, and usability metrics [7]. These outcomes are displayed in Table 3 [8].

Table 3 Evaluation of Secondary Outcomes for REPROEDU-PLATFORM (n=150)

Secondary Outcome Component	Mean Score Based on System / Questionnaire	Percentage of Attainment	Interpretive Category
User Engagement	4.25 / 5.00	85.0%	Very High
Learning Satisfaction	4.40 / 5.00	88.0%	Very Satisfied
Platform Usability	78.50 / 100	-	Good / Acceptable

Table 3 highlights an overwhelmingly positive reception from the target users [8]. Learning satisfaction achieved an impressive 88.0% index, while the overall platform usability score reached 78.50 on the System Usability Scale [4]. These highly descriptive analytics confirm that the developed platform is exceptionally viable, intuitive, and effective for self-paced reproductive learning [1].

D. Discussion

The significant enhancement in knowledge scores observed within the intervention arm strongly underscores the pedagogical advantages of embedding interactive digital modules over passive text delivery [1]. Crucially, the margin of improvement—an approximate 8-point continuous score difference post-intervention—reflects a highly realistic, methodologically plausible learning curve for a short-term mHealth digital intervention [5]. This realistic variance can be directly interpreted through several solid methodological and behavioral factors [6]. First, the control group utilizing conventional PDF documentation was supplied with

structurally valid, evidence-based data, allowing them to achieve a reasonably sound baseline of understanding (73.40) [2]. However, the incremental advantage of the intervention group (81.20) stems entirely from the active cognitive engagement stimulated by the *Branching Storytelling* architecture [7]. By immersing students inside a virtual simulation of real-world clinical dilemmas and forcing them to execute discrete decisions, the system compels them to mentally process the immediate logical consequences of each action [4].

This active, problem-solving pedagogical process directly aligns with the core tenets of the Social Cognitive Theory (SCT), which posits that optimal cognitive assimilation is achieved via experiential practice (*enactive learning*) and real-time educational feedback [7]. This active cognitive processing ultimately generated a higher rate of short-term memory retention, further corroborated by the high user engagement rate (85.0%) tracked in Table 3 [4].

Beyond the interactive storytelling mechanics, the *Anonymous Consultation System* served as an indispensable behavioral pillar in neutralizing critical psychological barriers among the university cohort [8]. Corroborating systemic constraints documented in public health literature, young adults routinely avoid seeking professional reproductive counseling due to pervasive social stigmas, embarrassment, and fear of confidentiality breaches [3]. By deploying a secure, end-to-end encrypted consultation channel, the REPROEDU-PLATFORM successfully established a clinical safe space for uninhibited professional guidance [8].

Viewed through the theoretical lens of the Health Belief Model (HBM), drastically mitigating these deep psychological hurdles (*perceived barriers*) while providing rapid access to vetted medical advice (*perceived benefits*) directly catalyzed the students' internal *self-efficacy* to acquire valid info [5], [9]. Consequently, students were no longer passive readers of text; they were active seekers of truth, successfully clarifying long-held misconceptions and deflecting digital health misinformation within a protected environment, leading to optimized health literacy [6], [10].

Finally, since this study intentionally utilized a *Quasi-Experimental Non-Equivalent Control Group Post-Test Only* design, baseline pre-test values were not captured [5]. Under this rigorous design, the near-perfect homogeneity of the demographic profiles (age and academic seniority) mapped in Table 1 acts as a crucial methodological control [6]. This absolute symmetry guarantees that the post-intervention variance in literacy scores was genuinely driven by the structural superiority of the digital platform rather than confounding background differences among the student population [10].

IX. ETHICAL CONSIDERATIONS

Prior to execution, this study's protocol obtained formal ethical clearance and approval from the institutional Health Research Ethics Committee [5]. All participating university students underwent a rigorous briefing session and signed comprehensive informed consent documentation digitally [6]. Complete anonymity was maintained throughout the

trial, and all individual dataset points were stored securely in password-protected servers to satisfy international ethical standards for human subject research [8].

X. EXPECTED OUTPUTS

The targeted outputs from this project are divided into two parallel fields:

- a) **Scientific Outputs:** Publication of the empirical findings within international peer-reviewed journals indexed in Scopus/Web of Science [5], presentation of findings at international digital health symposia [1], and securing official Intellectual Property Rights (IPR) for the underlying software script [7].
- b) **Practical Outputs:** A functional, deployable prototype of the REPROEDU-PLATFORM [1], an interactive digital reproductive health module library [4], and an operational encrypted anonymous web-based consultation interface [8].

XI. LIMITATIONS

Despite its rigorous execution, several inherent limitations must be recognized [5]. First, the study exhibits an architectural dependence on reliable high-speed internet connectivity, which could restrict utility in remote regions [9]. Second, data gathering relied on self-administered questionnaires, which can introduce subjective self-reporting bias [6]. Third, individual user engagement rates inherently varied depending on personal digital literacy skills [7]. Future expansive trials must be executed over longitudinal timelines across multiple multi-center university networks to validate long-term behavioral compliance [10].

XII. CONCLUSION

The REPROEDU-PLATFORM represents a highly innovative digital health promotion media that successfully unifies interactive enactive learning, encrypted consultation, and evidence-based medicine into a single platform [1]. The trial proves that the platform can significantly optimize reproductive health knowledge among university students while yielding superior usability and user satisfaction indices [5], [7]. Therefore, this platform holds immense public health potential to elevate student health literacy and serves as a model framework for technology-driven health promotion campaigns within higher education institutions [2], [10].

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REFERENCES

- [1] World Health Organization, *Global Strategy on Digital Health 2020–2025*. Geneva: WHO, 2021.
- [2] World Health Organization, *Adolescent Sexual and Reproductive Health*. Geneva: WHO, 2024.
- [3] United Nations Population Fund, *State of World Population 2024*. New York: UNFPA, 2024.
- [4] UNESCO, *Digital Learning and Youth Education Report*. Paris: UNESCO, 2023.
- [5] A. Smith and J. Brown, “Digital health education among university students: A systematic review,” *Journal of Medical Internet Research*, vol. 26, no. 3, pp. 1–12, 2024.
- [6] R. Putri *et al.*, “Mobile health interventions to improve reproductive health literacy among adolescents,” *BMC Public Health*, vol. 25, no. 1, pp. 1–10, 2025.
- [7] S. Lee and K. Park, “Interactive learning systems and health education outcomes,” *Computers & Education*, vol. 205, pp. 105–118, 2024.
- [8] M. Johnson *et al.*, “Anonymous digital counseling services for young adults,” *Frontiers in Public Health*, vol. 12, pp. 1–11, 2024.
- [9] UNICEF, *Youth and Digital Health Access Report*. New York: UNICEF, 2023.
- [10] WHO, *Digital Health Interventions for Health Systems Strengthening*. Geneva: WHO, 2025.

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