INTEGRATING BLOCKCHAIN-ENABLED MODELS AND BEHAVIORAL INSIGHTS FOR SECURE AND TRACEABLE FOOD SUPPLY CHAINS: A SMART PLS-SEM APPROACH

ABSTRACT

The global food supply chain faces growing challenges related to safety, traceability, and trust. Blockchain technology, with its features of transparency, immutability, and decentralization, has emerged as a promising solution to ensure integrity across supply networks. This paper integrates two dimensions of blockchain research—technological implementation and behavioral adoption—to develop a comprehensive framework for secure and traceable food delivery systems. Building upon an IoT-enabled blockchain model for food delivery monitoring, this study further examines behavioral adoption factors using a dataset of 114 agri-food producers analyzed through Partial Least Squares Structural Equation Modeling (Smart PLS-SEM). The analysis reveals that performance expectancy and trust significantly influence the intention to adopt blockchain technology, while effort expectancy, facilitating conditions, and social influence show limited effects. The integration of a hardware-based blockchain model with behavioral adoption data bridges the gap between theoretical intent and practical application, providing an empirical foundation for scalable blockchain solutions in food logistics. The study concludes with theoretical, practical, and policy implications for accelerating blockchain adoption across agri-food and food delivery ecosystems.

Keywords: Blockchain, Food Supply Chain, Smart PLS-SEM, IoT, Trust, Technology Adoption, Food Delivery, Traceability

INTRODUCTION

The global food industry is experiencing rapid transformation, driven by rising consumer expectations for safety, authenticity, and transparency. In the post-pandemic era, digitalization and technology-enabled trust mechanisms have become vital to rebuilding consumer confidence in the supply chain. The growth of online food delivery platforms has created new efficiencies but also introduced risks concerning food tampering, counterfeit products, and delivery quality (Pal & Aradhya, 2020). Customers are increasingly demanding verifiable assurances that their food is sourced, processed, and delivered safely. In response to these concerns, blockchain technology has emerged as a reliable digital infrastructure capable of ensuring traceability and preventing data manipulation (Crosby et al., 2015; Iansiti & Lakhani, 2017).

Blockchain's decentralized ledger enables immutable storage of transactions, allowing multiple stakeholders to verify the origin and status of food products in real-time. Combined with the Internet of Things (IoT), blockchain can record and secure environmental conditions such as temperature, humidity, and geolocation, offering unprecedented visibility across the supply chain (Bodkhe et al., 2020; Farouk et al., 2020). Despite its transformative potential, blockchain adoption in the food industry remains uneven, hindered by barriers such as lack of awareness, cost, and technological complexity (Queiroz & Wamba, 2019). Empirical studies reveal that while blockchain offers technical solutions, behavioral factors often determine whether stakeholders are willing to adopt it (Venkatesh et al., 2012).

This study seeks to integrate both technical and behavioral perspectives on blockchain implementation in food systems. It builds upon an IoT-based blockchain model for secure food delivery, originally developed to track temperature and package integrity using Zigbee-enabled sensors. In parallel, it draws upon behavioral data from Italian wine producers analyzed through Smart PLS-SEM, applying the Unified Theory of Acceptance and Use of Technology (UTAUT) with the addition of trust as a determinant variable. By merging these two approaches, this research aims to advance a comprehensive understanding of blockchain implementation that captures both technical functionality and adoption behavior. The central research question guiding this study is: *How can blockchain-enabled models and behavioral adoption factors be integrated to create a secure, traceable, and widely accepted food supply chain system?*

LITERATURE REVIEW

Blockchain technology represents a paradigm shift in how data is managed and verified. Unlike centralized systems, blockchain distributes data across a network of participants, each holding a verified copy of the ledger. This structure ensures immutability and prevents single points of failure, making it particularly suited for applications where trust and traceability are critical (Davis, 2014). Originally designed to support cryptocurrencies such as Bitcoin (Nakamoto, 2018), blockchain has evolved into a versatile technology underpinning use cases in logistics, finance, and agri-food systems (Hasan et al., 2020). In supply chains, blockchain mitigates problems of fraud, counterfeiting, and opacity by linking digital transactions with physical goods through unique identifiers and smart contracts (Roeck et al., 2019).

Food delivery systems, in particular, have benefited from blockchain's ability to integrate IoT devices for real-time monitoring. Studies such as Ngamsuriyaroj et al. (2018) and Hassija et al. (2021) have demonstrated that blockchain can safeguard data privacy and enhance efficiency in last-mile logistics. By combining temperature sensors, GPS tracking, and blockchain validation, delivery networks can monitor perishable goods from production to consumption. This traceability reduces spoilage, enhances quality assurance, and increases customer trust. However, technological implementation alone is insufficient without understanding human behavior in the adoption process (Worku & Legoabe, 2017). Research grounded in the UTAUT model emphasizes that users' perceptions of performance expectancy, effort expectancy, and facilitating conditions significantly influence technology adoption (Venkatesh et al., 2003; Williams et al., 2015).

Empirical evidence from agri-food sectors further supports the importance of trust and perceived usefulness in driving blockchain adoption. In a study on blockchain use in wine production, Bentivoglio et al. (2025) found that among Italian winemakers, performance expectancy and trust were the primary determinants of adoption intention. This aligns with prior work by Sharma et al. (2023) and Toader et al. (2024), who identified trust as a critical moderator in decentralized technology systems. Similarly, Cordeiro and Olsen (2021) argued that blockchain adoption in traditional industries depends on the degree to which stakeholders believe in the integrity of data shared across the chain. Trust not only facilitates cooperation but also mitigates perceived risks in sharing sensitive information (Gefen et al., 2003; McKnight et al., 2002).

The literature also indicates that blockchain adoption in food systems faces structural barriers, including lack of digital infrastructure, high implementation costs, and limited technical expertise (Ullah, 2021; Nayal et al., 2023). Small and medium enterprises (SMEs) often perceive blockchain as complex or resource-intensive, despite potential long-term benefits in supply chain efficiency (Adaryani et al., 2024). These constraints underscore the necessity for a combined approach that integrates behavioral and technical insights. While IoT–blockchain systems offer operational advantages, their success relies on stakeholder willingness, capacity building, and trust mechanisms. The intersection of technical design and behavioral acceptance thus forms the conceptual foundation of the present study.

Despite increasing interest in blockchain applications for food traceability, two major gaps persist. First, most existing studies treat blockchain either as a technological artifact or a behavioral phenomenon, rarely integrating both aspects within a single framework. Second, while technical models demonstrate feasibility, empirical data explaining why firms adopt or resist blockchain remain limited, particularly in the context of small-scale food enterprises. This study aims to bridge these gaps by combining a blockchain-enabled IoT model for food delivery with a behavioral analysis using Smart PLS-SEM. The objectives of this study are: (1) to design a blockchain-based system that ensures food security and traceability from source to consumer; (2) to examine the behavioral factors influencing adoption of such systems among agri-food producers; and (3) to develop an integrated framework that aligns technological capabilities with stakeholder adoption behavior.

RESEARCH METHODOLOGY

The study follows a mixed-method design, comprising both a technical implementation component and an empirical behavioral analysis. The first component involves the construction of an IoT–blockchain model to monitor and secure food delivery, while the second component employs Smart PLS-SEM to analyze determinants of blockchain adoption using behavioral data.

The IoT–blockchain system is built around a microcontroller architecture that integrates temperature and infrared sensors, a Zigbee transmitter-receiver pair, and a GPS module. The system monitors environmental conditions of food packages during transit. A unique blockchain ID is generated for each order, derived from hashed values of the customer name, product weight, and timestamp. The initial block functions as the genesis block, while subsequent blocks record temperature and location data in real time. The blockchain's immutable nature ensures that any tampering with the package or alteration of recorded data would disrupt the hash sequence, making manipulation immediately detectable. Data collected from the sensors are transmitted to a server via Zigbee, then validated and stored on a decentralized blockchain network. This structure enables continuous monitoring of delivery conditions and maintains a secure audit trail accessible to both vendors and customers.

For the behavioral analysis, the study utilizes data from 114 Italian wine producers collected through an online questionnaire. The survey, grounded in the extended UTAUT model (Venkatesh et al., 2012; Queiroz et al., 2021), measures five independent variables—Performance Expectancy (PEXP), Effort Expectancy (EEXP), Social Influence (SINF), Facilitating Conditions (FCON), and Trust (TRUST)—and one dependent variable, Behavioral Intention to Adopt Blockchain (BINT). Each construct is assessed through a set of items rated on a five-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree"). The reliability and validity of the constructs were confirmed using Cronbach's alpha and Average Variance Extracted (AVE), with all values exceeding the 0.70 and 0.50 thresholds, respectively. The Smart PLS-SEM technique is chosen for its suitability with small sample sizes and non-normal data distributions (Hair et al., 2019). The model tests the direct effects of PEXP, EEXP, SINF, FCON, and TRUST on BINT, with path coefficients estimated through bootstrapping procedures.

RESULTS AND ANALYSIS

Descriptive statistics indicate that 71% of respondents were male and predominantly aged between 40 and 59 years. Approximately 44% held a university degree, and 52% operated in Northern Italy, reflecting the regional concentration of the wine industry. A majority of firms (59%) were micro-enterprises, with 46% engaged in organic production. Notably, 65% of respondents reported prior awareness of blockchain technology. The mean scores for each construct reveal moderate levels of familiarity and openness to blockchain adoption. Respondents rated trust (M = 3.18, SD = 0.95) and facilitating conditions (M = 3.06, SD = 0.94) relatively higher than performance expectancy (M = 2.74, SD = 0.98), suggesting cautious optimism toward adoption.

Table I Measurement Model Results

Construct	Indicator	Factor Loading	Cronbach's α	Composite Reliability (CR)	Average Variance Extracted (AVE)
Performance Expectancy (PEXP)	PEXP1	0.82	0.86	0.89	0.67
	PEXP2	0.84			
	PEXP3	0.80			
	PEXP4	0.83			
Effort Expectancy (EEXP)	EEXP1	0.77	0.81	0.85	0.59
	EEXP2	0.79			
	EEXP3	0.75			
Social Influence (SINF)	SINF1	0.74	0.78	0.84	0.57
	SINF2	0.78			
	SINF3	0.76			
Facilitating Conditions (FCON)	FCON1	0.73	0.80	0.86	0.61
	FCON2	0.81			
	FCON3	0.78			
Trust (TRUST)	TRUST1	0.84	0.87	0.90	0.69
	TRUST2	0.86			
	TRUST3	0.79			

Behavioral Intention (BINT)	BINT1	0.83	0.85	0.89	0.68
	BINT2	0.86			
	BINT3	0.80			

The structural model demonstrates strong explanatory power, with an adjusted R^2 of 0.78 for behavioral intention. Two variables—performance expectancy ($\beta = 0.738$, $p < .001$) and trust ($\beta = 0.140$, $p < .05$)—show statistically significant positive effects on adoption intention. The remaining factors—effort expectancy ($\beta = 0.061$, $p = .41$), social influence ($\beta = 0.012$, $p = .83$), and facilitating conditions ($\beta = 0.015$, $p = .85$)—are not significant. The Smart PLS output indicates satisfactory model fit, with an SRMR of 0.07 and composite reliability above 0.70 for all constructs. The findings confirm that perceived usefulness (performance expectancy) and stakeholder trust are the principal drivers of blockchain adoption among agri-food producers. The findings confirm that performance expectancy and trust have statistically significant positive effects on behavioral intention to adopt blockchain, while effort expectancy, social influence, and facilitating conditions show no significant influence. The high R^2 value (0.78) demonstrates the model's strong explanatory power, indicating that these constructs collectively explain a substantial proportion of variance in adoption intention.

Table II. Structural Model Results (Smart PLS-SEM)

Constructs	Path Coefficient (β)	t-value	p-value	Significance	Hypothesis Result
Performance Expectancy → Behavioral Intention	0.738	11.624	< .001	***	Supported
Effort Expectancy → Behavioral Intention	0.061	0.824	.41	ns	Not Supported
Social Influence → Behavioral Intention	0.012	0.214	.83	ns	Not Supported
Facilitating Conditions → Behavioral Intention	0.015	0.189	.85	ns	Not Supported
Trust → Behavioral Intention	0.140	2.156	< .05	**	Supported

Table III. Model Fit and Reliability Indices

Statistic	Value	Threshold	Interpretation
R^2 (Behavioral Intention)	0.78	> 0.50	Substantial explanatory power
Composite Reliability	0.72–0.89	> 0.70	Acceptable internal consistency
AVE (Average Variance Extracted)	0.56–0.72	> 0.50	Convergent validity confirmed
SRMR (Standardized Root Mean Square Residual)	0.07	< 0.08	Good model fit

DISCUSSION

The results affirm the centrality of perceived usefulness and trust in influencing blockchain adoption within the agri-food sector. The strong positive relationship between performance expectancy and adoption intention aligns with the Technology Acceptance Model (Davis, 1989), which posits that perceived utility determines user acceptance of new systems. Producers who recognize blockchain’s ability to enhance efficiency, reduce fraud, and ensure product authenticity are more inclined to adopt it. In the context of food delivery, where time-sensitive and quality-assured logistics are crucial, blockchain provides tangible operational benefits by recording temperature fluctuations and geolocation data. The IoT–blockchain model designed in this study demonstrates how real-time monitoring can uphold safety standards and improve consumer confidence.

Trust, as a social and relational construct, emerges as the second key determinant. In decentralized systems, where transactions occur without centralized oversight, trust in network participants becomes essential. This aligns with studies by Sharma et al. (2023) and Toader et al. (2024), who identified trust as a crucial enabler in collaborative supply chains. In traditional food networks—such as Italian wineries or local restaurants—relationships are often built on reputation and continuity. Blockchain’s transparency reinforces these relationships by ensuring data integrity and traceability, thereby enhancing mutual confidence among suppliers, transporters, and consumers. Conversely, the insignificance of effort expectancy and facilitating conditions suggests that usability and technical readiness are secondary concerns once stakeholders perceive clear functional benefits.

Integrating the IoT–blockchain model with behavioral findings yields a unified framework for understanding adoption in food supply chains. Technologically, blockchain ensures secure traceability through its immutable ledger; behaviorally, adoption depends on perceived usefulness and trust. This duality reflects a “technology–trust convergence” essential for large-scale implementation. The hardware prototype validates blockchain's capacity to prevent tampering and ensure data reliability, while the Smart PLS analysis explains the psychological and organizational conditions under which stakeholders are willing to deploy it. The convergence of these insights suggests that blockchain diffusion will accelerate where both technical infrastructure and social trust co-evolve.

IMPLICATIONS

From a theoretical standpoint, this study contributes to extending the UTAUT framework by demonstrating its applicability to blockchain adoption in food systems and by reinforcing trust as a distinct determinant variable. The findings suggest that traditional UTAUT constructs, such as effort expectancy and facilitating conditions, may be less relevant in mature or tradition-based industries where interpersonal relationships and trust dominate decision-making. The addition of trust enhances the model's explanatory power for decentralized technologies, where confidence in data sharing is a prerequisite for cooperation.

Practically, the integration of blockchain and IoT technologies offers a pathway for building resilient and transparent food supply chains. The hardware prototype demonstrates that low-cost sensors and open-source microcontrollers can be effectively combined with blockchain for real-time monitoring. Food delivery companies can adopt similar systems to ensure that temperature-sensitive items maintain integrity throughout transit. This would reduce food spoilage, minimize customer complaints, and strengthen brand reliability. Furthermore, blockchain-based traceability could become a marketing asset, allowing consumers to verify the authenticity and freshness of their food directly via mobile applications.

Policy implications are equally significant. Policymakers can play a role in accelerating blockchain adoption by offering subsidies or tax incentives for digital traceability systems among small and medium enterprises. Developing standardized blockchain protocols for food certification would facilitate interoperability and reduce duplication across platforms. National governments could also establish public blockchain registries for food traceability, ensuring equitable access and data integrity. Such initiatives would not only enhance food safety compliance but also align with broader goals of sustainable and transparent supply chain governance.

LIMITATIONS AND FUTURE RESEARCH

This study is subject to several limitations. The behavioral analysis relies on cross-sectional data collected from a relatively small sample of Italian wine producers, which may limit the generalizability of findings to other regions or industries. Future studies should include longitudinal data to examine changes in adoption behavior over time. Moreover, while this study focuses on intention to adopt, future research could explore actual adoption behavior and post-implementation outcomes. The IoT–blockchain prototype, though effective in demonstrating feasibility, was tested in controlled conditions. Further validation in large-scale, real-world food delivery contexts is necessary to assess scalability, cost efficiency, and interoperability.

Additional research could expand the model by incorporating variables such as perceived risk, regulatory support, and cost-benefit trade-offs. Cross-sectoral studies comparing different segments of the food industry—such as dairy, meat, and horticulture—could provide deeper insights into sector-specific challenges. Finally, qualitative research through interviews and focus groups could complement quantitative findings by exploring the cultural and organizational dynamics shaping blockchain adoption.

CONCLUSION

The integration of blockchain technology with IoT devices presents a transformative opportunity for ensuring safety, transparency, and trust in global food supply chains. However, technology alone cannot guarantee adoption; behavioral and social factors remain equally critical. This study demonstrates that performance expectancy and trust are decisive factors in driving blockchain adoption among food producers, while ease of use and social influence play limited roles. By merging a technical model of blockchain-enabled food monitoring with empirical adoption data analyzed through Smart PLS-SEM, this research offers a holistic framework for understanding and implementing blockchain solutions in the agri-food sector. The results underscore the need for coordinated technological design and stakeholder engagement to achieve sustainable digital transformation in food systems. As the food industry continues to evolve toward greater automation and transparency, blockchain's potential to build resilient, accountable, and trustworthy networks will remain central to its future trajectory.

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