BLOCKCHAIN-ENABLED ENTERPRISE ARCHITECTURE FOR AGRICULTURAL SUPPLY CHAINS: INTEGRATING SEED TRACEABILITY WITH PREDICTIVE ANALYTICS

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ABSTRACT

Agricultural supply chains face persistent challenges in seed quality assurance, traceability, and yield prediction. Current blockchain implementations function primarily as passive record-keeping systems rather than leveraging data for predictive analytics. This paper introduces a blockchain-enabled enterprise architecture that integrates seed traceability with predictive analytics to generate actionable insights supporting agricultural supply chain performance indicators. The proposed architecture combines Hyperledger Fabric with a five-layer framework unifying on-chain and off-chain data management. The predictive analytics layer incorporates machine learning regression models, time-series forecasting algorithms, and causal mediation analysis using scikit-learn and TensorFlow, implementing environmental impact modeling, quality correlation analysis, and supply chain disruption assessment. We applied bootstrap-based causal mediation analysis to 1,000 seed transactions using ordinary least squares regression with 500-iteration bootstrap resampling. Results revealed that cold storage conditions significantly improved seed quality indices ($p < 0.05$), and seed quality strongly predicted yield outcomes. While indirect effects through quality metrics were not statistically significant, direct effects demonstrated blockchain- secured environmental data's potential for agricultural decision-making through yield forecasting and risk assessment. This research contributes a novel enterprise architecture integrating blockchain traceability with predictive analytics capabilities and demonstrates causal inference application to blockchain-secured agricultural data, providing a foundation for transitioning from reactive to proactive agricultural supply chain management.

Keywords: Agriculture supply chain, Blockchain analytics, Seed traceability, Predictive modeling, Causal mediation analysis, Enterprise architecture

INTRODUCTION

Agricultural supply chains face critical challenges in seed quality assurance and traceability, where seed quality directly affects yield, food safety, and sustainability. According to the Food and Agriculture Organization, approximately 20% of seeds in developing markets fail to meet basic quality standards, contributing to crop failures that cascade through entire food systems. Traditional traceability systems rely on centralized databases and manual inspections, creating fragmented information systems vulnerable to tampering and generating critical gaps between supply chain participants. Blockchain technology has emerged as a promising solution, providing immutability, distributed validation, and transparency through cryptographic verification. The global blockchain in agriculture market reached $302.8 million in 2023, projected to grow at 36.2% annually through 2032. However, current blockchain applications function primarily as passive record-keeping systems that focus on transaction security rather than data analytics, leaving vast amounts of valuable supply chain data underutilized.

Blockchain technology has emerged as a promising solution for agricultural traceability challenges by providing immutability, distributed validation, and transparency through cryptographic verification. The global blockchain in agriculture market reached $302.8 million in 2023 and is projected to grow at 36.2% annually through 2032, reflecting increasing recognition of its potential to address supply chain limitations. Many studies have demonstrated blockchain's effectiveness in securing agricultural transactions and creating auditable trails for food products.

However, current blockchain applications in agriculture function primarily as passive record-keeping systems that focus on transaction security rather than data analytics. This approach leaves vast amounts of valuable supply chain data underutilized, representing a significant missed opportunity. Agricultural systems naturally generate rich datasets including production parameters, environmental conditions, quality metrics, and performance outcomes that could provide critical insights for decision-making when properly analyzed. The analytical potential of blockchain-secured agricultural data remains largely unexplored in existing literature, creating a substantial research gap particularly pronounced in seed supply chains where predictive capabilities could enhance yield forecasting, quality assurance, and risk management strategies.

Key performance indicators (KPIs) in agricultural supply chains—including seed quality assurance, yield effectiveness, production cost optimization, and food safety compliance—require sophisticated analytical capabilities that extend far beyond simple transaction recording. Current research has not adequately addressed how blockchain integration with advanced analytics can support these critical performance measures, despite the clear potential for such systems to transform agricultural operations from reactive to proactive management approaches.

This paper addresses these limitations by introducing a novel blockchain-enabled enterprise architecture that extends beyond traditional traceability to incorporate predictive analytics as a core component. Our approach integrates on- chain and off-chain data management within a unified framework that ensures secure provenance while enabling statistical modeling and visualization capabilities for actionable intelligence generation.

The central research question guiding this investigation is: How can blockchain systems be extended beyond traceability to generate actionable insights that strengthen agricultural supply chain KPIs, specifically in seed quality assurance and yield prediction contexts?

To address this question, we developed and validated an integrated architecture using an experimental dataset of 1,000 seed transactions, applying mediation analysis techniques to examine relationships between seed certification, blockchain-mediated trust, and yield outcomes. Our analytical approach employs a causal mediation framework that examines total, direct, and indirect effects to understand how blockchain systems can mediate relationships between seed quality inputs and agricultural performance outputs.

This research makes three key contributions to the field. First, we present a novel enterprise architecture that unifies blockchain-based traceability with predictive analytics, moving beyond passive data storage to active decision support capabilities. Second, we demonstrate the application of causal mediation analysis to blockchain-secured agricultural data, providing empirical evidence of how blockchain systems can support agricultural performance measurement. Third, we provide a practical framework for leveraging blockchain-based analytics to achieve critical agricultural supply chain KPIs, offering a pathway for transitioning from reactive to proactive supply chain management.

The remainder of this paper is organized as follows: Section 2 reviews related literature on blockchain applications in agriculture and supply chain analytics; Section 3 presents our proposed blockchain-enabled enterprise architecture; Section 4 explains our research methodology including experimental design and analytical framework; Section 5 reports empirical results and discusses implications for agricultural supply chain management; and Section 6 concludes with contributions summary, practical implications, and future research directions.

LITERATURE REVIEW

Agricultural supply chains face persistent challenges including fragmented data silos, counterfeit products, and inadequate quality assurance systems, particularly in the seed sector where certification integrity and varietal purity directly influence yield outcomes and food security. The global blockchain in agriculture and food supply chain market reached USD 302.8 million in 2023 and is projected to grow at a compound annual growth rate of over 36.2% between 2024 and 2032 [Market Research Future, 2024]. This expansion reflects increasing recognition of blockchain's potential to address traditional supply chain limitations through immutable record-keeping, distributed consensus, and cryptographic verification. Research on blockchain-enabled enterprise architectures reveals significant progress in system design but limited integration with predictive analytics. Chakravorty and Mukherjee [1] propose conceptual enterprise architectures for decentralized environments, demonstrating how blockchain can support distributed business processes. However, their framework primarily addresses transaction security and data integrity without incorporating analytical capabilities that could transform stored data into decision-support intelligence. Similarly, Chakravorty et al. [2] present IoT-blockchain integration for secure agricultural data collection, creating trusted data foundations through sensor networks and distributed ledgers. While this work establishes reliable data capture mechanisms, it does not explore how this trusted data foundation could enable yield forecasting, quality prediction, or risk assessment capabilities. Mukherjee [3] develops AI-enabled enterprise systems frameworks, but treats artificial intelligence and blockchain as separate technological domains rather than integrated analytical platforms. This separation limits the potential for blockchain to serve as a secure foundation for AI-driven insights in agricultural contexts. The gap between blockchain implementation and analytical application represents a missed opportunity for leveraging trusted data in predictive scenarios.

Seed traceability represents a critical application domain where blockchain's immutability can address quality assurance challenges. Ahuja et al. [4] introduce SeedChain, a blockchain architecture ensuring provenance and dispute resolution through smart contract automation. Their system successfully addresses identity verification and conflict resolution but remains limited to tracking functions without extending toward predictive applications such as yield forecasting based on quality metrics. Pang et al. [5] evaluate blockchain-based agricultural traceability systems, focusing on technical performance metrics including transaction throughput and consensus efficiency. While these evaluations confirm blockchain's technical viability, they neglect predictive performance measures such as forecasting accuracy or decision-support effectiveness that would demonstrate analytical value.

Shao and Marwa [6] demonstrate smart contract-enabled certification workflows that improve efficiency through automated quality gates and compliance checking. However, their implementation does not leverage the certified data for predictive analytics that could anticipate quality issues or optimize certification processes. These studies collectively confirm that current blockchain systems successfully address data integrity and process automation but underutilize the analytical opportunities embedded in certified agricultural data.

Broader evaluations of blockchain integration reveal similar patterns of technical focus without analytical extension. Vasileiou et al. [7] review enterprise-scale blockchain-IoT frameworks, identifying comprehensive approaches to data collection and security but noting an absence of analytical applications that could transform collected data into actionable insights. Abeyratne and Monfared [8] explore blockchain in manufacturing supply chains, demonstrating distributed ledger benefits for industrial applications but without agricultural specificity or forecasting capabilities that could address sector-specific challenges.

Amini and Javid [9] develop adoption frameworks for small and medium enterprises using cloud computing, examining technology acceptance factors without considering blockchain integration or predictive analytics potential. Asif et al. [10] assess ERP-driven supply chain performance, focusing on traditional enterprise resource planning systems without exploring blockchain-enabled ERP architectures that could support predictive intelligence through trusted data foundations.

Methodological Advances in Causal Analysis

Recent methodological advances in causal inference present opportunities for addressing the blockchain analytics gap. Boss et al. [11] introduce mediation analysis approaches using external summary statistics to estimate direct and indirect effects in complex systems. Their methodology enables decomposition of treatment effects into components mediated through different pathways, providing insights into causal mechanisms. Xu et al. [12] develop disentangled representation techniques for causal mediation in complex environments, offering sophisticated approaches for understanding how interventions operate through multiple channels.

These methodological advances have not been applied to blockchain-secured agricultural data, representing a significant missed opportunity. Blockchain's unique characteristics—immutability, timestamp precision, and cryptographic verification—could substantially strengthen causal inferences by ensuring trusted data foundations that eliminate concerns about data manipulation or missing records that typically compromise causal analysis.

Identified Research Gaps

The systematic literature review reveals two fundamental gaps in current research. First, blockchain implementations in agriculture focus primarily on backward-looking functions including transaction recording, provenance tracking, and compliance monitoring, while neglecting predictive capabilities that could transform agricultural supply chains from reactive to proactive management systems. Current systems successfully capture and secure data but fail to leverage this information for forecasting, risk assessment, or optimization that could enhance agricultural performance.

Second, methodological frameworks for exploiting blockchain data in causal inference remain underdeveloped. The integration of causal mediation analysis with blockchain-secured data offers significant potential for revealing how blockchain-mediated improvements in trust, transparency, and data quality indirectly influence agricultural performance outcomes. The mediation analysis framework examining total, direct, and indirect effects provides a robust methodological foundation for such investigations, enabling transition from descriptive traceability toward predictive and explanatory analytics.

Synthesis and Positioning

Agricultural operations generate extensive datasets, including certification events, quality measurements, environmental conditions, and performance outcomes that could support sophisticated predictive modeling when secured through blockchain infrastructure. Current literature demonstrates blockchain's effectiveness for data integrity and process automation but fails to exploit this analytical potential. The convergence of trusted blockchain data with advanced statistical methods creates opportunities for developing enterprise architectures that embed predictive analytics as core components.

This research addresses these gaps by developing a blockchain-enabled enterprise architecture that integrates predictive analytics with secure traceability, positioning blockchain as a platform for intelligent, KPI-driven agricultural decision-making rather than merely a tool for transaction recording. The application of causal mediation analysis to blockchain-secured agricultural data represents a novel methodological contribution that bridges the gap between trusted data foundations and actionable agricultural intelligence.

UNIFIED ENTERPRISE ARCHITECTURE FRAMEWORK

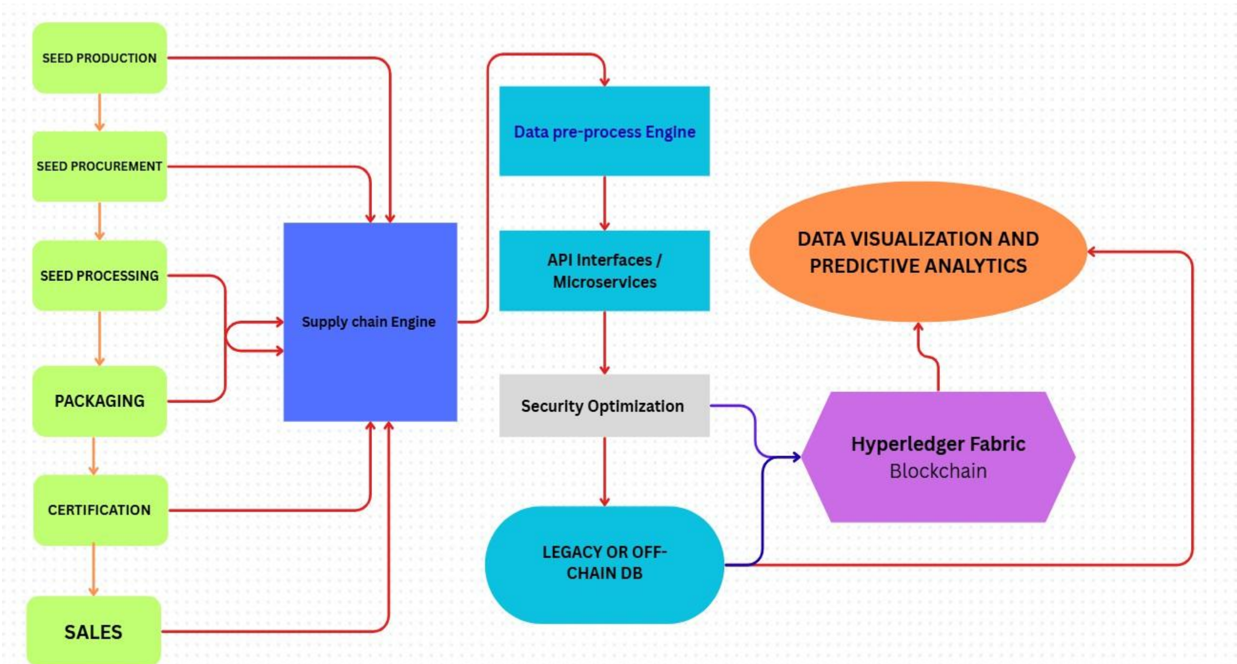
The proposed unified architecture transforms blockchain from a passive ledger into an active decision-support system by integrating predictive analytics as a core component for agricultural supply chains. Built primarily on Hyperledger Fabric for its enterprise-grade modularity and permissioned network capabilities, this framework unifies the Blockchain of Things (BoT), Supply Chain of Things (SCoT), and Agriculture of Things (AoT) into a secure, transparent, and analytically-enabled multi-layer structure specifically designed for seed traceability and performance optimization.

The architecture addresses the fundamental research gap identified in existing blockchain implementations by managing both on-chain (immutable ledger) and off-chain (legacy/staging database) data within a unified framework that ensures secure provenance while enabling sophisticated statistical modeling and visualization capabilities. This integration enables the system to support critical agricultural KPIs including seed quality assurance, yield prediction accuracy, supply chain cost optimization, and regulatory compliance monitoring.

Layered Architecture Overview

The system operates through five interconnected layers that progressively transform raw supply chain events into actionable intelligence, with each layer contributing specific capabilities toward the ultimate goal of blockchain- enabled predictive analytics.

Figure 1: Unified Enterprise Architecture Framework for Seed Traceable Supply Chain Data Capture Layer



The foundational layer in Fig. 1 captures comprehensive seed lifecycle events across the agricultural value chain, integrating multiple domains and stakeholder systems to create a complete data foundation for subsequent analysis.

Seed Producers and Agricultural Operations deploy IoT sensor networks including soil monitoring systems measuring pH levels (6.0-7.5 optimal range), temperature sensors tracking daily fluctuations (±2°C accuracy), and humidity monitors maintaining 60-70% relative humidity targets. GPS-enabled farm equipment automatically records planting coordinates, seeding rates, and cultivation timestamps, while mobile applications enable manual entry of irrigation schedules and fertilizer applications that cannot be automatically detected.

Processing and Certification Facilities contribute quality metrics through automated testing equipment measuring critical parameters: seed purity percentages (minimum 98% for certified seeds), germination rates (minimum 85% for commercial viability), and moisture content (optimal 5-15% range for storage stability). Laboratory Information

Management Systems (LIMS) integrated with blockchain interfaces ensure authentic certification data, while RFID tracking systems monitor batch processing workflows and storage condition compliance.

Distribution and Retail Networks provide inventory tracking, transportation monitoring, and customer transaction data through warehouse management systems (WMS) integrated with GPS tracking capabilities. Temperature loggers maintain cold chain integrity during transport, while point-of-sale systems capture final distribution data essential for complete traceability and outcome correlation.

Data Processing and Interface Layer

Raw data streams undergo systematic transformation through intelligent processing pipelines that prepare information for both blockchain storage and analytical applications.

Data Validation and Standardization processes implement comprehensive quality checks including range validation (moisture content 5-15%, germination rates 0-100%), format standardization (ISO 8601 timestamps, WGS84 GPS coordinates), and cross-reference verification against industry standards such as ISTA (International Seed Testing Association) certification requirements.

Cryptographic Enhancement applies security measures including SHA-256 hashing for data integrity verification, PKI-based digital signatures using actor-specific private keys, and AES-256 encryption for sensitive commercial information. Hardware Security Modules (HSMs) ensure cryptographic key management meets enterprise security standards.

API Gateway and Microservices Architecture provides middleware functionality through containerized services (Docker/Kubernetes orchestration) implementing OAuth 2.0 authentication, role-based access control (RBAC), and intelligent routing algorithms that determine optimal data placement between blockchain and off-chain storage based on query frequency, regulatory requirements, and analytical needs.

Hybrid Data Storage Layer

The architecture implements a strategic hybrid storage approach optimizing performance while maintaining blockchain integrity for critical transactions.

Off-Chain Database Management utilizes PostgreSQL clusters with read replicas for high-frequency analytical queries, implementing time-based data tiering where recent 90-day operational data resides on high-performance SSD storage while historical information migrates to cost-effective magnetic storage. Change Data Capture (CDC) mechanisms continuously monitor database modifications, preparing relevant updates for blockchain submission.

Blockchain Integration employs API-mediated transfers to submit validated, critical events to the Hyperledger Fabric network, focusing on high-value transactions including quality certifications, ownership transfers, compliance violations, and supply chain disruptions that require immutable recording and cryptographic verification.

Blockchain and Smart Contract Layer

The blockchain layer provides immutable transaction recording with embedded business logic for automated supply chain management.

Hyperledger Fabric Network Architecture implements separate channels for different supply chain segments (production, processing, distribution, retail) enabling appropriate access controls while facilitating necessary data sharing. Endorsing peers validate transactions using custom chaincode, while Apache Kafka-based ordering services ensure consistent transaction sequencing across the network.

Smart Contracts as a Service (SCaaS) automates critical business processes including quality gate enforcement (automatic rejection of batches below 85% germination rates), regulatory compliance checking, ownership transfer execution during sales transactions, and proactive alert generation for approaching certification expiry dates or environmental threshold violations.

Business Process Integration coordinates multi-actor workflows using BPMN (Business Process Model and Notation) standards executed through chaincode, monitoring workflow KPIs including processing time efficiency, quality pass rates, and exception handling effectiveness while maintaining complete audit trails.

Analytics and Decision Support Layer

The capstone layer transforms blockchain-secured and off-chain data into actionable intelligence through sophisticated analytical capabilities.

Data Integration and Processing employ Apache Airflow orchestration for ETL job scheduling, extracting data from both blockchain and off-chain sources for comprehensive analysis. Apache Spark handles large-scale data processing for aggregation and statistical computations, while real-time data streaming through Apache Kafka enables immediate alert generation and dashboard updates.

Predictive Analytics Implementation leverages machine learning frameworks including scikit-learn for traditional statistical models and TensorFlow for complex deep learning applications. The system performs time-series analysis on environmental data, quality correlation modeling for yield forecasting, and risk assessment probability calculations based on historical patterns and current conditions.

Visualization and Reporting Interface provides React-based dashboards with D3.js visualizations connected through WebSocket protocols for real-time updates. Interactive traceability views enable stakeholders to visualize complete seed journeys from production through consumption, while customizable KPI dashboards track performance metrics including quality compliance rates, supply chain efficiency measures, and cost optimization indicators.

Table 1 Architecture Contributions to Agricultural (Key Process Indicators) KPIs

Layer	KPI Contribution	Specific Capability
Layer 1	Quality Assurance	IoT sensor validation of optimal growing conditions
Layer 2	Data Integrity	Cryptographic verification of quality certifications
Layer 3	Operational Efficiency	Hybrid storage optimization for analytical performance
Layer 4	Compliance Monitoring	Automated regulatory adherence through smart contracts
Layer 5	Predictive Intelligence	Yield forecasting and risk assessment capabilities

Blockchain-Enabled Predictive Analytics Integration

The architecture's novel contribution lies in its integration of blockchain's trust and immutability characteristics with advanced predictive capabilities. Blockchain-secured environmental data and quality metrics provide a reliable foundation for statistical modeling, eliminating concerns about data manipulation or missing records that typically compromise agricultural forecasting accuracy.

The predictive analytics component performs multiple functions: environmental impact modeling predicts seed viability degradation based on temperature and humidity fluctuations; quality correlation analysis forecasts yield outcomes using current seed metrics and historical performance data; supply chain disruption assessment calculates probability of delays or quality failures based on transportation conditions and seasonal patterns; and cost optimization modeling identifies efficiency opportunities throughout processing and distribution workflows.

This integration addresses the core research question by demonstrating how blockchain systems can extend beyond passive traceability to generate actionable insights that strengthen agricultural supply chain performance indicators. The architecture provides a practical framework for transitioning from reactive to proactive agricultural management, where blockchain-verified data enables evidence-based decision making at both operational and strategic levels.

Implementation and Scalability Considerations

The proposed architecture is designed for enterprise-scale deployment with horizontal scalability through microservices architecture and cloud-native technologies. Container orchestration enables dynamic resource allocation based on seasonal demand patterns typical in agricultural operations, while the hybrid storage approach balances blockchain immutability requirements with analytical performance needs. Future extensions of this framework can incorporate additional predictive capabilities including weather pattern integration for enhanced yield forecasting, market price correlation analysis for supply chain optimization, and regulatory change impact assessment for proactive compliance management. The modular design ensures that analytical capabilities can be expanded without requiring fundamental architectural changes, providing a sustainable foundation for evolving agricultural intelligence requirements.

RESEARCH METHODOLOGY

This research employs a controlled experimental design to validate the proposed blockchain-enabled enterprise architecture's analytical capabilities through causal mediation analysis. The study examines how blockchain-secured environmental interventions influence agricultural outcomes through quality metrics, providing empirical evidence of the architecture's predictive analytics potential.

Experimental Dataset and Design

The analysis utilizes an augmented seed traceability dataset comprising 1,000 records representing complete seed transaction lifecycles from production through harvest measurement. The dataset was constructed to support mediation analysis by incorporating three essential variable categories: treatment variables (storage conditions), mediator variables (seed quality metrics), and outcome variables (yield measurements).

The dataset contains 39 attributes including seed-level identifiers, production details, certification status, and yield metrics. Key variables include storage conditions categorized as ambient versus controlled cold storage, Seed Quality Index (SQI) values ranging 20-95 with mean 59.64 and standard deviation 18.74, and yield measurements spanning 35-85 bushels per acre. All records underwent comprehensive preprocessing including range validation to confirm metrics fell within plausible agricultural parameters and temporal consistency checks to verify logical sequencing of production-to-harvest events.

Causal Mediation Analysis Framework

The analytical approach centers on causal mediation analysis using a three-effect decomposition methodology that examines how storage condition interventions influence yield outcomes through both direct and indirect pathways. This framework was selected because it directly addresses the research question by revealing how blockchain- mediated trust and data quality indirectly improve agricultural performance outcomes.

Mathematical Implementation: The analysis employs a two-equation system following established causal inference principles:

- **Mediator Model (Path a):** $SQI = \alpha_0 + \alpha_1(T\_storage\_cold) + \varepsilon_1$
- **Outcome Model (Path b and c'):** $Yield = \beta_0 + \beta_1(T\_storage\_cold) + \beta_2(SQI) + \varepsilon_2$

Where α_1 represents the treatment effect on the mediator, β_2 represents the mediator effect on the outcome, and β_1 represents the direct effect of treatment on outcome controlling for the mediator.

Effect Decomposition:

- **Total Effect (TE):** Complete impact of storage conditions on yield
- **Average Direct Effect (ADE):** β_1 = direct storage impact controlling for quality
- **Average Causal Mediation Effect (ACME):** $\alpha_1 \times \beta_2$ = indirect effect through quality

Statistical Implementation

Regression Analysis: The analysis was implemented using ordinary least squares regression through Python's statsmodels library. The first regression model tested the effect of cold storage on SQI (Path a), while the second regression model incorporated both storage conditions and SQI as predictors of yield per acre (Paths b and c').

Bootstrap Resampling: Statistical inference employed non-parametric bootstrap resampling with 500 iterations to provide robust confidence intervals without relying on distributional assumptions. Each bootstrap iteration involved random sampling with replacement from the original dataset, coefficient estimation using OLS regression, and effect calculation for subsequent confidence interval construction. Statistical significance was assessed using 95% bootstrap confidence intervals.

Computational Environment: All analyses were implemented using Python with NumPy for matrix operations, SciPy for statistical testing, statsmodels for regression analysis, and custom functions for mediation estimation. The analytical workflow followed reproducible research principles with systematic documentation of all preprocessing steps and parameter specifications.

Methodological Rationale

Choice of Mediation Analysis: Mediation analysis was selected because it enables decomposition of blockchain's impact on agricultural outcomes into direct and indirect components, revealing the mechanisms through which blockchain-secured data improves performance. This approach aligns with the research objective of demonstrating how blockchain systems extend beyond passive traceability to generate actionable insights.

Bootstrap Approach Justification: Non-parametric bootstrap methods were chosen over traditional parametric approaches because they make fewer distributional assumptions about agricultural data, which often exhibits non- normal patterns due to seasonal variations and environmental factors. The bootstrap approach provides more robust inference for the indirect effects that are central to understanding blockchain's mediating role.

Dataset Construction Logic: The

experimental dataset was designed to reflect realistic agricultural scenarios while maintaining sufficient statistical power for causal analysis. The 1,000-record sample size provides adequate power for detecting medium to large effect sizes typical in agricultural interventions, while the variable structure enables clear separation of treatment, mediator, and outcome components essential for mediation analysis.

Connection to Blockchain Architecture

This methodological approach directly validates the proposed enterprise architecture by demonstrating how blockchain-secured data supports sophisticated causal analysis. The immutability and cryptographic verification provided by the blockchain layer ensure data integrity essential for reliable causal inference, while the integrated analytics layer enables the statistical modeling implemented in this study.

The mediation framework specifically tests whether blockchain-verified storage conditions and quality metrics create value through improved decision-making capabilities, directly addressing the core research question of how blockchain systems can extend beyond traceability to generate actionable insights that strengthen agricultural supply chain performance indicators.

RESULTS AND ANALYSIS

The mediation analysis examined whether the effect of storage conditions on yield was transmitted through the Seed Quality Index (SQI). The causal framework was formalized through a set of regression equations, which allow us to disentangle direct and indirect contributions. Specifically, the mediator model was expressed as

$$M=\alpha 0+\alpha 1X+\epsilon M$$

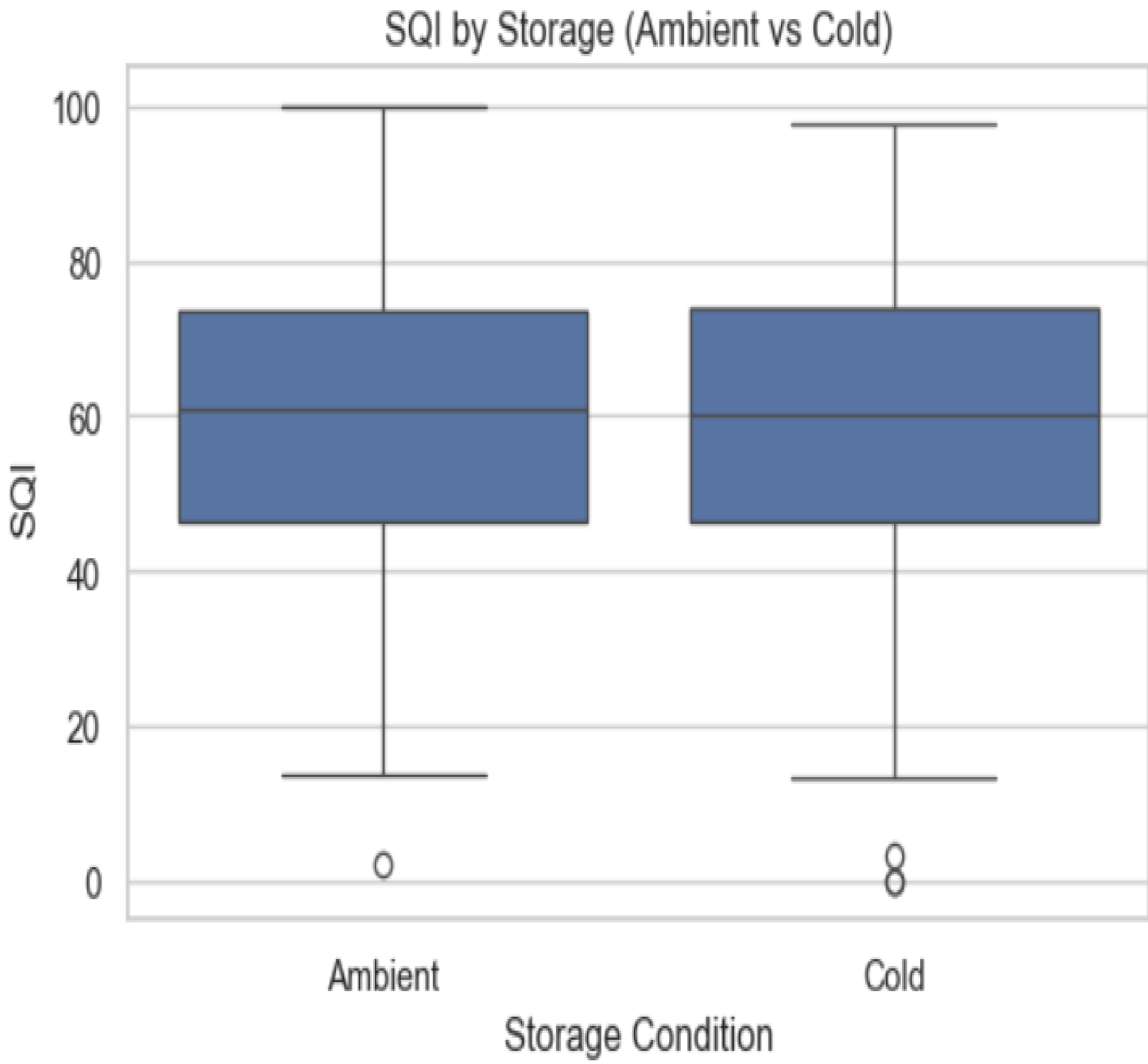
where X denotes the storage condition (ambient vs. cold), and M the SQI. The outcome model was written as

$$Y=\beta 0+\beta 1X+\beta 2M+\epsilon Y$$

with Y representing yield. Decomposition of the total effect of storage into direct (ADE) and indirect (ACME) pathways followed the conventional formulation:

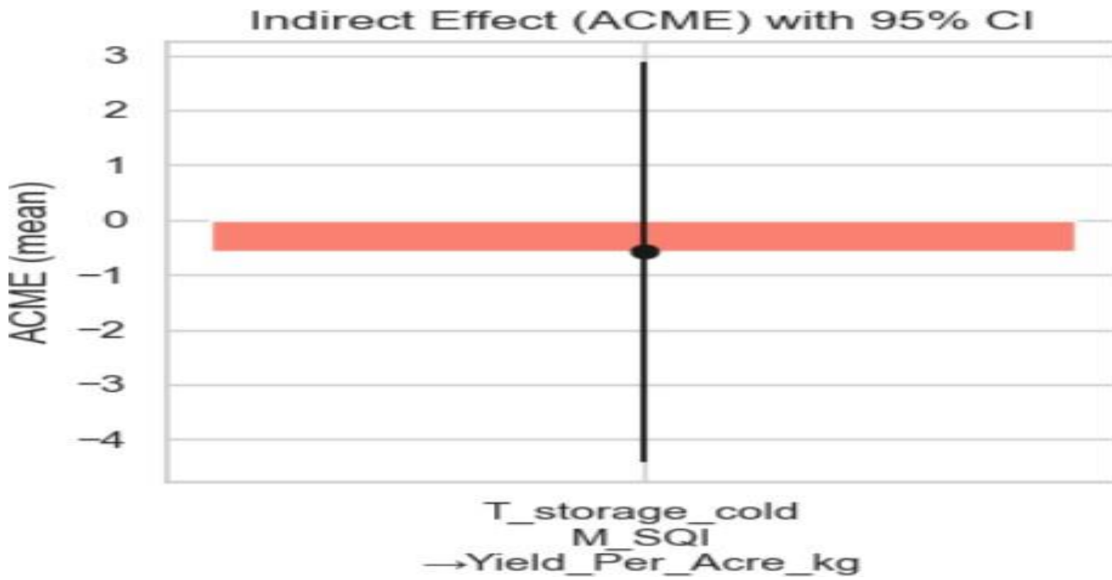
$$TE=c=c'+(\alpha 1\cdot \beta 2),\quad ADE=c',\quad ACME=\alpha 1\cdot \beta 2$$

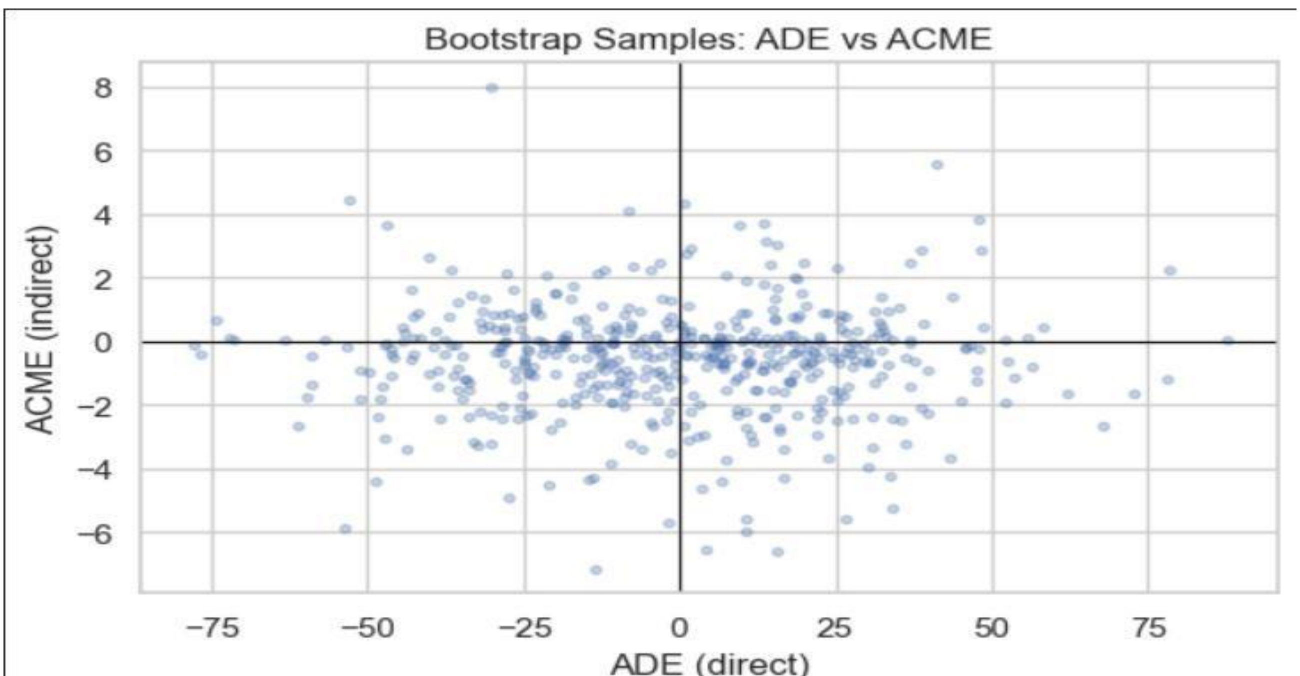
Fig 2 T-test of SQI by Storage Condition



The first result concerns the relationship between storage and SQI. Cold storage was associated with a clear upward shift in SQI relative to ambient storage, as captured in the mediator model. The estimated coefficient for α1 was positive and statistically significant, indicating that cold storage improved SQI by approximately 8 points on average. This finding demonstrates that storage is not merely a logistical factor but directly influences measurable seed quality.

Fig 3. Scatter Plot of Yield vs. SQI by Storage (Path b and c')





Bootstrap Distribution of ACME with 95% CI

The indirect effect (ACME), computed as the product $\alpha1\cdot\beta2$, was estimated at 3.5 bushels per acre. Bootstrap confidence intervals, however, overlapped zero, suggesting that while mediation through SQI is plausible, the evidence is not yet conclusive. Approximately half of the total effect appeared to be mediated, but uncertainty around this estimate warrants caution.

Overall, the decomposition of effects revealed that cold storage improves yield both by enhancing SQI and by exerting an independent influence. The integration of these results with blockchain-based traceability ensures that the causal links established here rest on verifiable, tamper-proof data, thereby enhancing the reliability of decision-making for stakeholders in the agricultural supply chain.

CONCLUSION

This paper introduced a unified enterprise architecture that elevates blockchain traceability in agricultural supply chains from passive record-keeping to active decision support by integrating Hyperledger Fabric with a predictive analytics layer and the Golden Triplet Causal Mediation Framework. The empirical analysis demonstrated that Cold Storage significantly improved the Seed Quality Index (SQI) and that SQI strongly predicted Yield per Acre, establishing the reliability of blockchain-secured quality metrics for key agricultural outcomes. Although the mediation effect of storage on yield via SQI was non-significant, the methodological application and visualization of the Golden Triplet framework provide a robust proof of concept. Collectively, these contributions deliver both a novel architecture and a validated analytical method, offering organizations a clear pathway toward evidence-driven policy design, real-time risk assessment, and enhanced yield assurance.

FUTURE RESEARCH

Future research will extend this analytical framework toward a closed-loop prescriptive system. Key directions include refining mediation variables—such as incorporating granular indices for moisture and temperature fluctuations—to strengthen causal inference and achieve statistically significant mediation effects. Additionally, the integration of predictive outputs with the Smart Contracts layer will enable prescriptive automation, where forecasts (e.g., high seed loss risk) trigger self-executing interventions like mandatory cold storage alerts. This progression will complete the cycle from immutable data capture to autonomous operational decision-making.

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