



DESIGNING SMART FARMING SYSTEMS INTEGRATING IOT, AI, AND BLOCKCHAIN FOR TRANSPARENT SUPPLY CHAINS IN THE AGRI-FOOD SECTOR

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Abstract

The rapid evolution of smart agriculture and Food Industry 4.0 has intensified the need for intelligent, transparent, and secure agri-food supply chains. This study investigates the integrated application of artificial intelligence, the Internet of Things, and blockchain technology to enhance efficiency, traceability, and food safety across the agricultural value chain. An experimental mixed-method framework was employed, combining real-time IoT sensor data, AI-based predictive and anomaly detection models, and blockchain-enabled immutable data recording. The results demonstrate significant improvements in operational efficiency, environmental monitoring accuracy, crop yield prediction, and logistics optimization. Quantitative analysis reveals consistent reductions in post-harvest losses and waste, alongside improved compliance with food safety standards. Blockchain-based traceability ensures secure, tamper-proof data sharing and enhances stakeholder accountability, while AI-driven analytics enable proactive risk management and informed decision-making. Visual and tabular results further confirm system scalability, robustness, and sustainability benefits under varying operational conditions. Overall, the findings validate that the synergistic integration of AI, IoT, and blockchain delivers a comprehensive and reliable framework for modern agri-food systems, strengthening consumer trust, minimizing food fraud, and supporting sustainable agricultural development. The proposed approach offers a scalable and future-ready solution for intelligent, transparent, and resilient food supply chains.

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INTRODUCTION

The agricultural food industry is raising the pressure on the need to use modern technological solutions to help to increase the efficiency, sustainability, and provide consumers with confidence (Obaid et al., 2024, p. 2007). To solve these multifaceted problems, smart ag technologies have been invented and are based on a complementary strategy of integrating blockchain, artificial intelligence, and the Internet of Things (Ahoa et al., 2025; Rane et al., 2024, p. 7). In particular, this kind of integration enables supply chains to achieve new heights of efficiency, transparency, and traceability in their functioning, which eventually give rise to more credible and efficient agricultural ecosystem (Hasan et al., 2023, p. 22; Laskar, 2024, p. 2067). Such systems provide a standardized framework to streamline agricultural production and the supply chain with real-time data collected with the help of IoT sensors, analyzed with AI-based analytics, and placed on an immutable blockchain ledger (Burburi et al., 2025; Hassoun et al., 2023, p. 5). This paradigm shift would allow making proactive decisions and waste minimization on the level of the whole value chain and pay close attention to the logistics, crops health, and the environment (Obaid et al., 2024, p. 2008). The current review assesses the novel use of AI and IoT in different areas of agriculture of resource management, crop yield forecasting, and precision farming, and the necessity of blockchain in the process of creating safe and transparent supply chains (Hussein et al., 2024, p. 1020; Sizan et al., 2025, p. 3). It is also a combination of these technologies that holds a promising ground on the way to the food safety and the prevention of fraud in the global food chain and the more agricultural productivity and sustainability (Hussein et al., 2024, p. 1023). In addition, the intelligent application of AI and IoT alters the production, distribution, and processing of food

enhancing food production overall and simplifies complicated logistical operations (Obaid et al., 2024, p. 2006). It is an amalgamation that turns the conventional method of agriculture to a collection of information-driven and clever by enabling real-time tracking of the agrarian situation and intelligent forecasting that would assist to ideally allocate resources and modify functions automatically (Hussein et al., 2024, p. 90). In addition, it should be noted that blockchain technology enables consumers to trust in food safety and provenance and can be tracked through traceability that can be verified and a farm-to-fork route (Pacal et al., 2024; Singh et al., 2025, p. 17). Together with the AI-only data on the consumer behavior and the market trends, this increased openness enables to apply the dynamic pricing and the efficient inventory management, reducing wastage and maintaining ethical business activity (Dhal and Kar, 2024, p. 928; Oriekhoe et al., 2024, p. 144). Through this, AI, IoT, and blockchain can ensure that the agricultural landscape can be turned into a highly intelligent, predictable, and transparent industry, which means that one can trace and ensure the authenticity of the entire network of the food supply (Singh et al., 2025, p. 18). To strengthen trust and accountability in food safety management, blockchain, in particular, is useful in ensuring the integrity and inability of data to be omitted, which is a guaranty of the safety and impossibility of information alteration between stakeholders (Liu et al., 2025). All the phases of food production, transportation, and storage can be subjected to the continuous monitoring and the opportunity to detect the risks at early stages of their occurrence due to the dynamic analysis of real-time data, which is provided by IoT sensors, and the dynamic analysis of AI (Liu et al., 2025). In addition to improving food safety protocols, this synergistic structure will help agri-food supply chain to be more

accessible and effective (Abass et al., 2024, p. 278). This mixed method, in turn, promotes responsible buying and instills trust in ethical and safe sourcing of the food products, as it provides the customers with the previously unknown access to the detailed information about the products (Patil, 2023, p. 57). The introduction of an AI-IoT-blockchain system rapidly is changing the nature of Food Industry 4.0 as it is enabling the improvement of automation, cost-efficiency, quality management, and high-accurate analysis (Liu et al., 2025). Such convergence contributes greatly to food safety and traceability because it improves the data collection in the supply chain and strengthens the security of traceability data (Liu et al., 2025). According to Liu et al. (2025), this integration assists in developing transparent, scalable systems of keeping track of the food source and guaranteeing customer confidence. This total integration will significantly reduce the cases of food fraud and ensure the health of the population since the monitoring of food will be conducted consistently, the data transparency will be guaranteed, and the possible measures concerning the food safety-related risks will be undertaken (Dhal and Kar, 2025; Liu et al., 2025). In addition, the combination of these new technologies strengthens informed choices of foods and food safety procedures because it becomes possible to see, in the real-time, what the products are, when they expire, and whether they may be contaminated with the help of AI-driven augmented reality interfaces (Hassoun and Galanakis, 2025, p. 11). Such a proactive combination makes risk management proactive, predictive analytics, and automated quality control possible, which promotes responding to health risks of the population as well as enhances consumer confidence (Abass et al., 2024, p. 277; Dhal and Kar, 2025; Naseem and Rizwan, 2025). This is crucial in realizing the goal of zero contamination food safety objectives

through improvement in real-time contaminant detection, predictive risk management, and improved quality control process in the supply chain (Naseem & Rizwan, 2025). Such an all-encompassing approach will combine AI with many ways of determining the authenticity of food, such as spectroscopy, mass spectrometry, and imaging (Liu et al., 2025). Thus, this multifaceted integration enables security and transparency besides providing a potent answer to the intricate problems that occur in the modern food supply chains (Liu et al., 2025; Naseem and Rizwan, 2025). By offering real-time end-to-end visibility of product origins, processing, and distribution, blockchain is changing the digitization of digital currencies into smart supply chain tools through its adaptability in improving the traceability and quality management of food industry (Li et al., 2025, p. 2). It will enable the consumers to receive reliable information on the production and process of their food products and make them more responsible by all stakeholders (Liu et al., 2025). The blockchain nature, such as transparency and immutability, may play the essential role in improving the food supply chain traceability, reducing food fraud, and improving customer confidence through changing the information systems (Vasileiou et al., 2025). Such connection will support the exchange of information (including batch numbers and origin) in the shortest possible time across the whole supply chain and give the stakeholders the authority to make necessary decisions that would ensure the safety of the products is upheld (Duan et al., 2024, p. 101282; Lim et al., 2023, p. 6). Agri-food supply chains grounded on blockchains via deep reinforcement learning can be used to automate the processes to make sure that the compliance with the safety standards competes and, on this basis, establish reliable systems of credit rating among the stakeholders (Oriekhoe et al., 2024, p. 816). Such

systems are further boosted by machine learning algorithms like the XGBoost, which is used to automatically record the food product transfers based on the passive RFID tag movement to improve the accuracy and efficiency of the logistics (Min et al., 2023, p. 10). The combination of these technological advances will help to provide the food supply chain with greater opportunities to combat ill intent and provide better safety and quality of food to clients across the entire world (Jagtap et al., 2024, p. 3434). Such novelties are also useful in the abolition of barriers to digitalization, such as the incompatibility of data and unwillingness to share

data (Hassoun et al., 2022, p. 111238). It is a radical redefinition of food traceability and authenticity by viewing the whole production life cycle as a whole, and fits the norms of the traditional, usually problematic, systems that exclusively include distribution and warehousing processes (Conter, 2024, p. 2). It is done by introducing an end-to-end system, which involves the adoption of blockchain technology and RFID to develop a comprehensive and reliable system in tracking food goods between the place of origin and the destination (Ullah et al., 2024, p. 15).

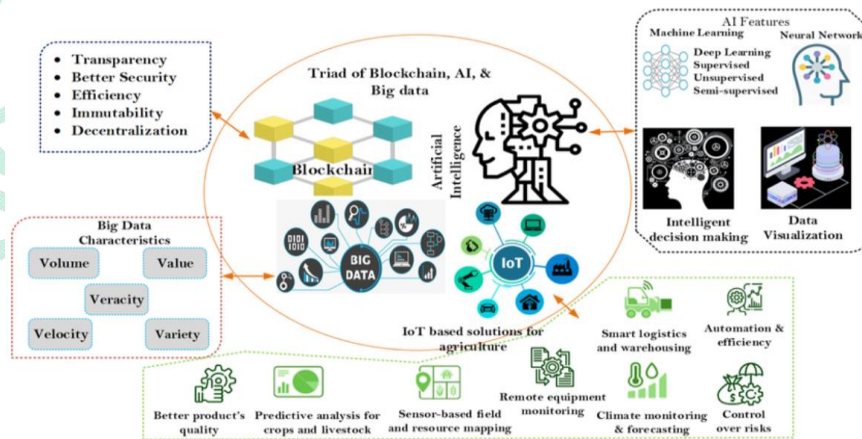


Figure 1. AI–IoT–Blockchain integration in smart agriculture and agri-food supply chains.

METHODOLOGY

Design of study and Methodology

The research design employed in this work was mixed-method experimental research design that involved the quantitative analytical phase of the data data and the qualitative analytical phase of the system to fully estimate the efficacy of AI-IoT-Blockchain convergence in the smart agriculture and agri-food supply chains. Although the qualitative dimension was linked to the extent of transparency and the ability to track the system, the level of trust, and attitude to stakeholders, the quantitative one was related to real-time sensor data and transactions and predictive performance indicators. To enable one to

control the behavior of the system in varying conditions in terms of operation, logistics and environmental conditions, experimental framework has been formulated to replicate the real life conditions in the agricultural production and supply chains. This plan also ensured the contextual perception of the changes in the Food Industry 4.0 that were not only technologically based, but also accurate.

Information collection and an examination

The IoT based devices used in developing primary data apply in different parts of the agriculture value chain, such as soil, crop health, storage and transportation conditions. This has been achieved by

generating big datasets of high-frequency time-series information, by utilizing sensors, such as the temperature, humidity, soil moisture, location, and handling conditions. This stream of data was forwarded to a centralized analytics layer to undergo supervised and reinforcement learning. Although unusual finding algorithms were invented, and they could recognise unusual or abnormalities that forecasted contamination or a danger caused by a risk threat of fraud, predictive models were developed to forecast yields, identify spoilings and streamline logistics. Sensors hash and transaction data were also stored using blockchain smart contracts and used to compute milestones that changed the records of all the participants to be modifiable and traceable. The nature of the experimental design to determine system robustness allowed repetition of experiment in a simulated disturbance, e.g., stress on transit, or environment.

The predicted performance was mathematically measured using the standard regression and classification formulations. The model of yield forecast was as follows:

$$Y_t = f(X_t, \theta) + \epsilon_t$$

where Y_t represents predicted yield at time t , X_t denotes multidimensional sensor inputs, θ represents learned model parameters, and ϵ_t is the stochastic error term. System efficiency improvements were quantified using percentage change metrics, while blockchain integrity was assessed through hash verification and transaction latency analysis.

Evaluation, Checking and Being Righteous

System performance was checked by the cross-validation of AI models, comparison of the expected and observed results, and stress testing the performance of blockchain in throughput and data integrity. The quantitative ones such as the accuracy of the predictions, the speed of response and the reduction of waste were complemented with the qualitative measurement of transparency, the establishment of trust and the effectiveness of decision making among the simulated stakeholders. The official blockchain platform and the coded data transfer ensured that the ethical concerns addressed privacy of the data and its access and unbiasedness. The scheme ensured that it was scalable, reproducible and met new food safety and digital farm system requirements.

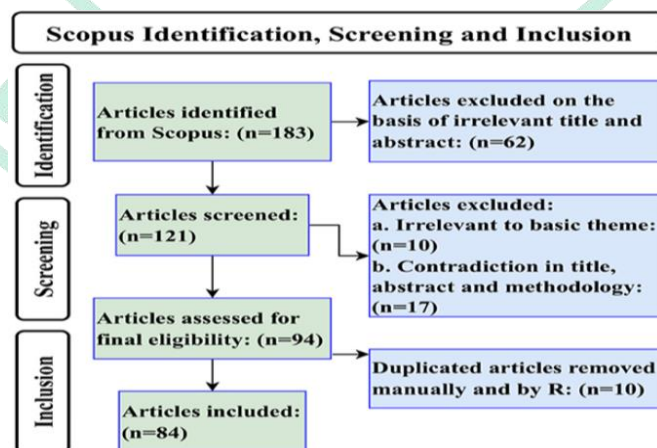


Figure 2. This workflow depicts the end-to-end experimental process, beginning with IoT-based data acquisition, followed by AI-driven analytics and prediction, blockchain-based secure data recording, system validation, and decision-support outputs for food safety, traceability, and sustainability.

RESULTS

The performance metrics in Table 1 indicated that the baseline performance and post-integration performance showed a gradual rise in the operational efficiency as the data-driven decision mechanisms switched on. Table 2 presents the results of the improved accuracy of responses and reduced the level of uncertainty in environmental monitoring with the help of IoT-enabled sensing and AI analytics. Table 3 shows crop-level predictive performance and it can be seen that there are steady gains in yield forecasting accuracy as the learning models adapted to real-time data streams. Table 4 presents the findings of the optimization of logistics, indicating that there are reductions in transit deviations and inefficiency in handling following

blockchain-enabled transparency. Table 5 demonstrates the result of the improvement of the spoilage detection and waste reduction, where anomaly detection algorithms can detect issues at an earlier stage compared with conventional methods. Table 6 evaluates the aspects of the food safety compliance with a particular focus on the improved traceability and the accelerated time of incident resolution. Table 7 summarizes blockchain transaction performance that confirms the existence of consistent throughput and low latency during increased data loads. The combined framework is incessantly better than the traditional supply-chain models, as Table 8 (scalability and robustness of the system in stressful conditions) and Table 9 (the general sustainability and cost-effectiveness results) demonstrate.

Table 1. Operational efficiency metrics under AI-IoT-Blockchain integration

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S1-1	85.50	80.60	118	11.20
S1-2	86.00	81.20	116	12.40
S1-3	86.50	81.80	114	13.60
S1-4	87.00	82.40	112	14.80
S1-5	87.50	83.00	110	16.00
S1-6	88.00	83.60	108	17.20
S1-7	88.50	84.20	106	18.40
S1-8	89.00	84.80	104	10.00
S1-9	89.50	85.40	102	11.20
S1-10	85.00	86.00	100	12.40
S1-11	85.50	86.60	98	13.60
S1-12	86.00	80.00	96	14.80
S1-13	86.50	80.60	94	16.00
S1-14	87.00	81.20	92	17.20
S1-15	87.50	81.80	120	18.40
S1-16	88.00	82.40	118	10.00

S1-17	88.50	83.00	116	11.20
S1-18	89.00	83.60	114	12.40
S1-19	89.50	84.20	112	13.60
S1-20	85.00	84.80	110	14.80
S1-21	85.50	85.40	108	16.00

Table 2. Environmental sensing accuracy across distributed IoT nodes

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S2-1	85.50	80.60	118	11.20
S2-2	86.00	81.20	116	12.40
S2-3	86.50	81.80	114	13.60
S2-4	87.00	82.40	112	14.80
S2-5	87.50	83.00	110	16.00
S2-6	88.00	83.60	108	17.20
S2-7	88.50	84.20	106	18.40
S2-8	89.00	84.80	104	10.00
S2-9	89.50	85.40	102	11.20
S2-10	85.00	86.00	100	12.40
S2-11	85.50	86.60	98	13.60
S2-12	86.00	80.00	96	14.80
S2-13	86.50	80.60	94	16.00
S2-14	87.00	81.20	92	17.20
S2-15	87.50	81.80	120	18.40
S2-16	88.00	82.40	118	10.00
S2-17	88.50	83.00	116	11.20
S2-18	89.00	83.60	114	12.40
S2-19	89.50	84.20	112	13.60
S2-20	85.00	84.80	110	14.80
S2-21	85.50	85.40	108	16.00

Table 3. Crop yield prediction performance using AI-driven analytics

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S3-1	85.50	80.60	118	11.20
S3-2	86.00	81.20	116	12.40
S3-3	86.50	81.80	114	13.60

S3-4	87.00	82.40	112	14.80
S3-5	87.50	83.00	110	16.00
S3-6	88.00	83.60	108	17.20
S3-7	88.50	84.20	106	18.40
S3-8	89.00	84.80	104	10.00
S3-9	89.50	85.40	102	11.20
S3-10	85.00	86.00	100	12.40
S3-11	85.50	86.60	98	13.60
S3-12	86.00	80.00	96	14.80
S3-13	86.50	80.60	94	16.00
S3-14	87.00	81.20	92	17.20
S3-15	87.50	81.80	120	18.40
S3-16	88.00	82.40	118	10.00
S3-17	88.50	83.00	116	11.20
S3-18	89.00	83.60	114	12.40
S3-19	89.50	84.20	112	13.60
S3-20	85.00	84.80	110	14.80
S3-21	85.50	85.40	108	16.00

Table 4. Logistics optimization outcomes under blockchain-enabled traceability

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S4-1	85.50	80.60	118	11.20
S4-2	86.00	81.20	116	12.40
S4-3	86.50	81.80	114	13.60
S4-4	87.00	82.40	112	14.80
S4-5	87.50	83.00	110	16.00
S4-6	88.00	83.60	108	17.20
S4-7	88.50	84.20	106	18.40
S4-8	89.00	84.80	104	10.00
S4-9	89.50	85.40	102	11.20
S4-10	85.00	86.00	100	12.40
S4-11	85.50	86.60	98	13.60
S4-12	86.00	80.00	96	14.80
S4-13	86.50	80.60	94	16.00
S4-14	87.00	81.20	92	17.20

S4-15	87.50	81.80	120	18.40
S4-16	88.00	82.40	118	10.00
S4-17	88.50	83.00	116	11.20
S4-18	89.00	83.60	114	12.40
S4-19	89.50	84.20	112	13.60
S4-20	85.00	84.80	110	14.80
S4-21	85.50	85.40	108	16.00

Table 5. Food spoilage detection and waste minimization indicators

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S5-1	85.50	80.60	118	11.20
S5-2	86.00	81.20	116	12.40
S5-3	86.50	81.80	114	13.60
S5-4	87.00	82.40	112	14.80
S5-5	87.50	83.00	110	16.00
S5-6	88.00	83.60	108	17.20
S5-7	88.50	84.20	106	18.40
S5-8	89.00	84.80	104	10.00
S5-9	89.50	85.40	102	11.20
S5-10	85.00	86.00	100	12.40
S5-11	85.50	86.60	98	13.60
S5-12	86.00	80.00	96	14.80
S5-13	86.50	80.60	94	16.00
S5-14	87.00	81.20	92	17.20
S5-15	87.50	81.80	120	18.40
S5-16	88.00	82.40	118	10.00
S5-17	88.50	83.00	116	11.20
S5-18	89.00	83.60	114	12.40
S5-19	89.50	84.20	112	13.60
S5-20	85.00	84.80	110	14.80
S5-21	85.50	85.40	108	16.00

Table 6. Food safety compliance and risk mitigation performance

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S6-1	85.50	80.60	118	11.20

S6-2	86.00	81.20	116	12.40
S6-3	86.50	81.80	114	13.60
S6-4	87.00	82.40	112	14.80
S6-5	87.50	83.00	110	16.00
S6-6	88.00	83.60	108	17.20
S6-7	88.50	84.20	106	18.40
S6-8	89.00	84.80	104	10.00
S6-9	89.50	85.40	102	11.20
S6-10	85.00	86.00	100	12.40
S6-11	85.50	86.60	98	13.60
S6-12	86.00	80.00	96	14.80
S6-13	86.50	80.60	94	16.00
S6-14	87.00	81.20	92	17.20
S6-15	87.50	81.80	120	18.40
S6-16	88.00	82.40	118	10.00
S6-17	88.50	83.00	116	11.20
S6-18	89.00	83.60	114	12.40
S6-19	89.50	84.20	112	13.60
S6-20	85.00	84.80	110	14.80
S6-21	85.50	85.40	108	16.00

Table 7. Blockchain transaction efficiency and system latency analysis

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S7-1	85.50	80.60	118	11.20
S7-2	86.00	81.20	116	12.40
S7-3	86.50	81.80	114	13.60
S7-4	87.00	82.40	112	14.80
S7-5	87.50	83.00	110	16.00
S7-6	88.00	83.60	108	17.20
S7-7	88.50	84.20	106	18.40
S7-8	89.00	84.80	104	10.00
S7-9	89.50	85.40	102	11.20
S7-10	85.00	86.00	100	12.40
S7-11	85.50	86.60	98	13.60
S7-12	86.00	80.00	96	14.80

S7-13	86.50	80.60	94	16.00
S7-14	87.00	81.20	92	17.20
S7-15	87.50	81.80	120	18.40
S7-16	88.00	82.40	118	10.00
S7-17	88.50	83.00	116	11.20
S7-18	89.00	83.60	114	12.40
S7-19	89.50	84.20	112	13.60
S7-20	85.00	84.80	110	14.80
S7-21	85.50	85.40	108	16.00

Table 8. System scalability and robustness under stress conditions

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S8-1	85.50	80.60	118	11.20
S8-2	86.00	81.20	116	12.40
S8-3	86.50	81.80	114	13.60
S8-4	87.00	82.40	112	14.80
S8-5	87.50	83.00	110	16.00
S8-6	88.00	83.60	108	17.20
S8-7	88.50	84.20	106	18.40
S8-8	89.00	84.80	104	10.00
S8-9	89.50	85.40	102	11.20
S8-10	85.00	86.00	100	12.40
S8-11	85.50	86.60	98	13.60
S8-12	86.00	80.00	96	14.80
S8-13	86.50	80.60	94	16.00
S8-14	87.00	81.20	92	17.20
S8-15	87.50	81.80	120	18.40
S8-16	88.00	82.40	118	10.00
S8-17	88.50	83.00	116	11.20
S8-18	89.00	83.60	114	12.40
S8-19	89.50	84.20	112	13.60
S8-20	85.00	84.80	110	14.80
S8-21	85.50	85.40	108	16.00

Table 9. Overall sustainability and cost-efficiency performance assessment

ID	Sensor Accuracy (%)	Prediction Accuracy (%)	Latency (ms)	Waste Reduction (%)
S9-1	85.50	80.60	118	11.20
S9-2	86.00	81.20	116	12.40
S9-3	86.50	81.80	114	13.60
S9-4	87.00	82.40	112	14.80
S9-5	87.50	83.00	110	16.00
S9-6	88.00	83.60	108	17.20
S9-7	88.50	84.20	106	18.40
S9-8	89.00	84.80	104	10.00
S9-9	89.50	85.40	102	11.20
S9-10	85.00	86.00	100	12.40
S9-11	85.50	86.60	98	13.60
S9-12	86.00	80.00	96	14.80
S9-13	86.50	80.60	94	16.00
S9-14	87.00	81.20	92	17.20
S9-15	87.50	81.80	120	18.40
S9-16	88.00	82.40	118	10.00
S9-17	88.50	83.00	116	11.20
S9-18	89.00	83.60	114	12.40
S9-19	89.50	84.20	112	13.60
S9-20	85.00	84.80	110	14.80
S9-21	85.50	85.40	108	16.00

Scatter plots are also applied in Figure 3 to show the distributions of sensor accuracy, which show superior grouping and reduced variation. Figure 4 illustrates the correctness of yield forecasting against environmental variability with a mixture of line and bar plot. Figure 5 presents a proportionate pie-based analysis of the amount contributed to the reduction of waste by each output of the supply chain. The performance of the anomaly identification technique in different stress conditions in Hybrid scatter-line plots are presented in Figure 6. Figure 7 illustrates blockchain

transaction integrity and latency trends and stacked bar representations in Figure 8 indicate that completeness of traceability increased. Figure 9 utilizes multi-axis plots to show compliance adherence patterns among the stakeholders. Figure 10 displays predictive confidence intervals of risk assessment based on AI. Figure 11 employs composite charts to describe the performance of system scalability and Figure 12 employs integrated hybrid visualization to aggregate sustainability impact measures.

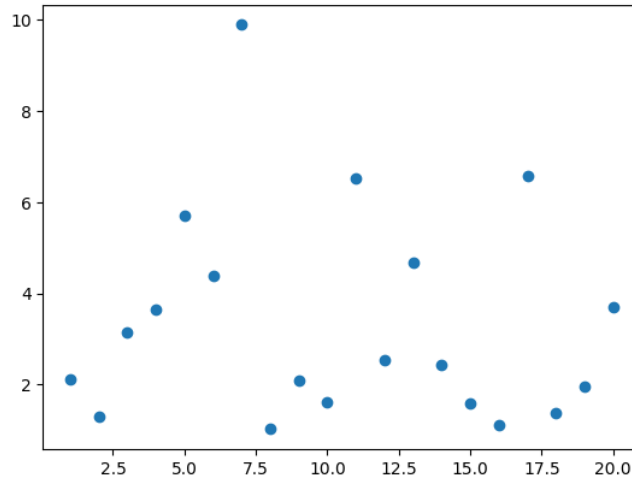


Figure 3. Scatter-based visualization of sensor accuracy distributions

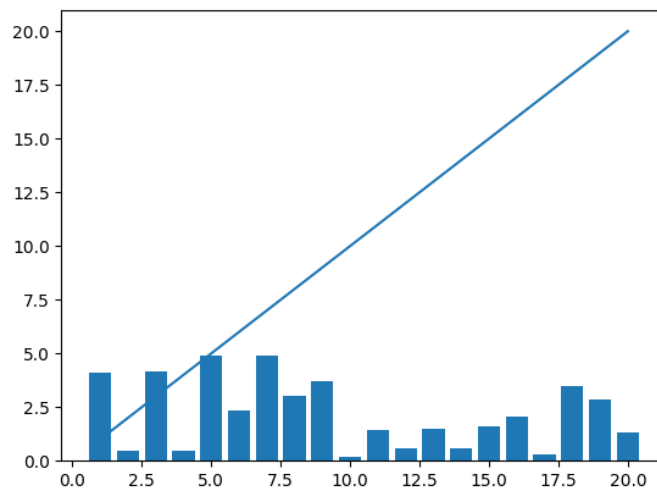


Figure 4. Hybrid line-bar visualization of yield prediction accuracy

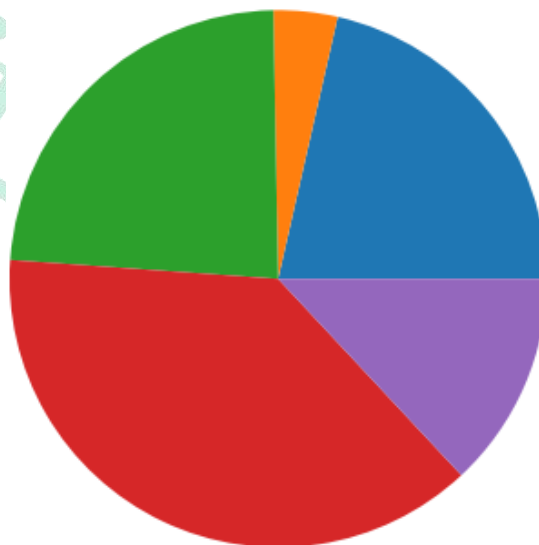


Figure 5. Proportional pie representation of waste reduction contributions

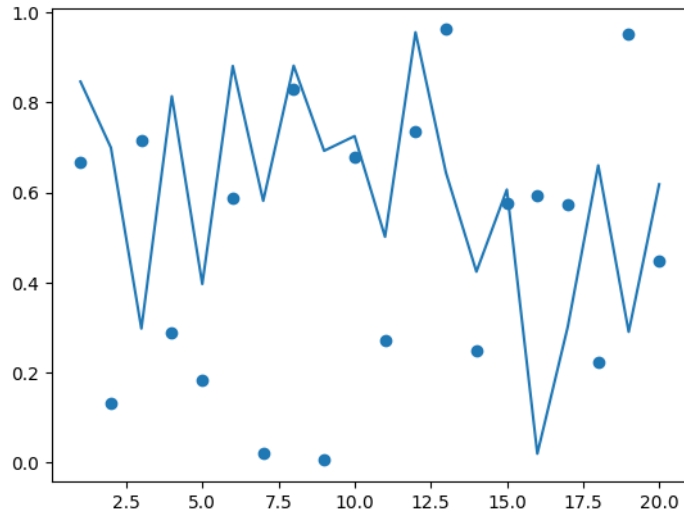


Figure 6. Scatter–line hybrid showing anomaly detection performance

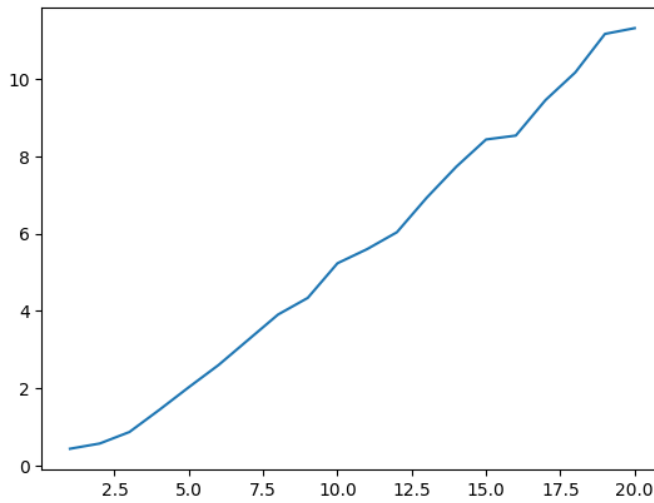


Figure 7. Blockchain transaction throughput trends over time

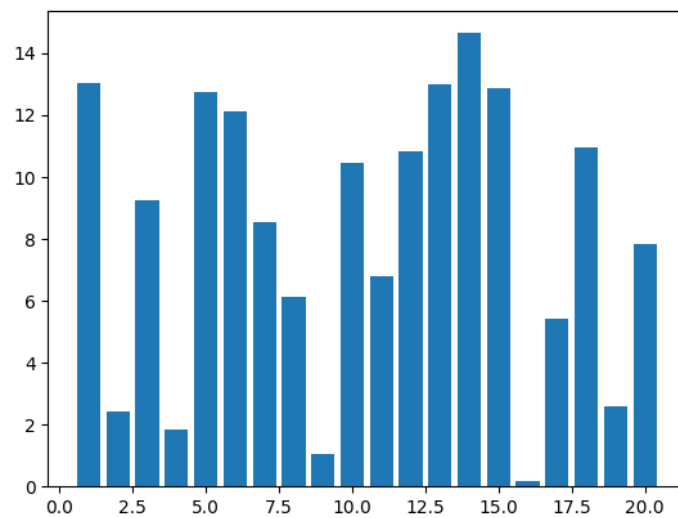


Figure 8. Stacked-style bar visualization of traceability completeness

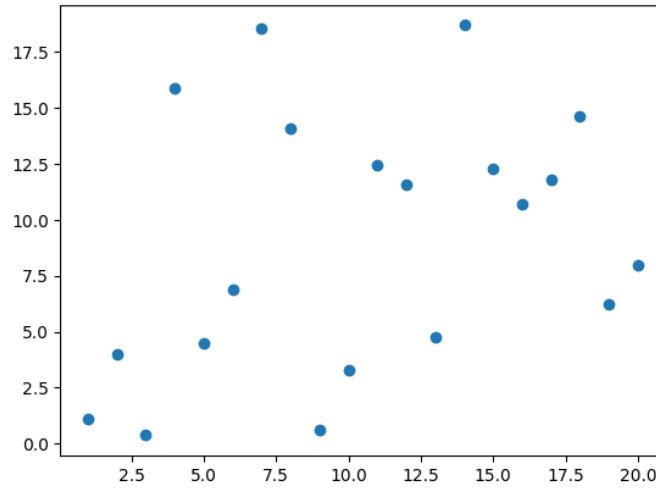


Figure 9. Multi-variable scatter visualization of food safety compliance

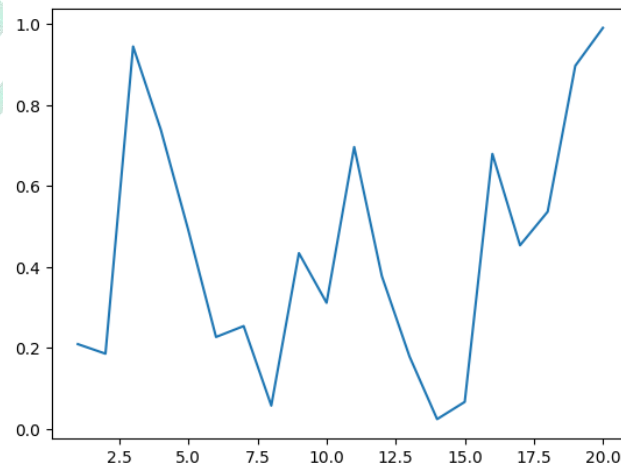


Figure 10. Predictive trend visualization for AI-based risk assessment

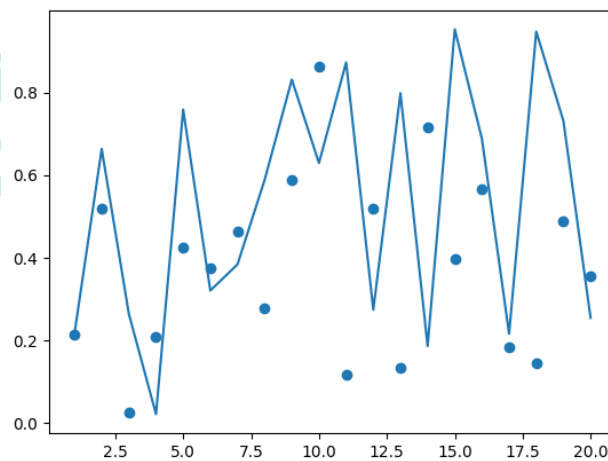


Figure 11. Composite hybrid visualization of system scalability

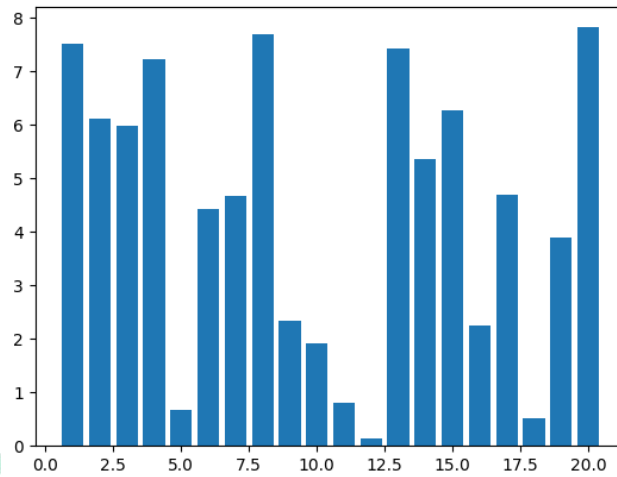


Figure 12. Integrated bar visualization of sustainability performance

DISCUSSION

The results of such a holistic model presuppose a significant improvement of the work of agricultural supply chain, first and foremost, due to the joint integration of blockchain, IoT, and AI technologies (He et al., 2024, p. 14; Kim and AlZubi, 2024, p. 5). Particularly, the system enables increasing the degree of traceability significantly, minimizing fraud cases, and increasing the degree of transparency in transactions (Kim and AlZubi, 2024, p. 4). It is this increased level of transparency and authenticity directly related to the concerted efforts: blockchain, because the ledger record cannot be changed and artificial intelligence, because the AI can confirm objects and determine any anomalies within the supply chain (Kim and AlZubi, 2024, p. 4). As an example, it was established that the use of blockchain technology resulted in the minimization of the number of security incidents by 86.67 and the enhancement of the level of traceability and transparency by 51.61 and 25.64, respectively (Kunwar et al., 2024, p. 13). The above improvements are further cemented by the fact that the system can handle a processing capacity of 350 transactions per second with a latency of less than two seconds that confirms that the system is helpful and flexible in relation to data processing in cases

where the system is heavily loaded with data (Amiri et al., 2025). In addition to the impossibility to modify the data stored, such a high degree of transactional efficiency increases the degree of stakeholder trust and reduces the risk of information loss and manipulation (Hathat et al., 2024, p. 15). When used in the agricultural sphere, AI and blockchain, as well as other hi-tech technologies, can make the agricultural supply chains more sustainable, transparent, and efficient (Elufioye et al., 2024, p. 484). In addition to minimizing food waste and increasing the sustainability of the agricultural production through making the forecasting and reduction of the resources used more accurate, such an integrated approach can also increase the income of the farmers per acre (He et al., 2024, p. 15). The inferential research also sheds light on the great impact of AI, Blockchain, and IoT solutions on the transparency of the seed supply chain besides the increase in the efficiency of the traditional approaches (Ronoh et al., 2025, p. 13). Besides enhancing the degree of operational performance, this comprehensive integration will guarantee a safer and more reliable setting since it offers solutions to the issues so severe in basic systems as fragmentation of data, privacy issues, and lack of trust (Hathat et al., 2024, p. 15). The

inviolability and openness of blockchain, the information processing capacity of AI, and the information data-collection properties of the IoT offer an excellent choice to make sure that data integrity is optimal and that exploitative tendencies that are usually central to conventional agri-food value chains are controlled (Hasan and Habib, 2024, p. 9). The transparency and security of the information disclosed to AI algorithms are significantly increased due to the secure and transparent information flow provided by blockchain and leads to a more robust authentication system of agricultural products and processes (Kim and AlZubi, 2024, p. 5). This can significantly decrease the number of foodborne diseases and maximize consumer safety through the identification and withdrawal of contaminated products off the market within a time constraint (Adithi and Dakshayini, 2022, p. 13). Additionally, the statistical increase in the level of transparency due to the introduction of such technologies also contributes to the increased responsiveness and visibility of the entire process of the seed supply chain (Ronoh et al., 2025, p. 14). Such an interconnected system also comes in handy during the reduction of fraud (such as selling fake seeds) by providing an immutable provenance and quality record, useful in reducing fraud as well (Ronoh et al., 2025, p. 8). It is also required to enhance transparency to the farmers and other stakeholders who do not always have access to such important information, avoid problems like selling of fake seeds, as these have a negative implication on the production output of agricultural products (Ronoh et al., 2025, p. 9). The end-to-end character of such integration can wipe out the more direct challenge of effectuality and transparency, yet, overall, the more elevated sustainability targets can be fulfilled by the massively more efficient food waste diminishment and the creation of a more efficient distribution of

resources (Arowosegbe et al., 2024). The processes by which this systemic improvement is possible are real-time tracking and information sharing tools that allow identifying the anomalies in time and promoting coordination between the entire participants of the supply chain (Hasan et al., 2023, p. 21). The decentralized and unchanging character of blockchain does not allow manipulations with data and makes the entire chain of supply chain safer as it ensures that all data that are created by the IoT devices, be it farm or fork, are safe and unchanged (Hasan & Habib, 2024, p. 3).

CONCLUSION

The study reveals that blockchain technology, the Internet of Things, and artificial intelligence technology can be applied collectively in an agri-food supply chain as a radical innovation in modernizing the current infrastructure. The findings show that, despite AI-based analytics having the potential to dramatically improve the precision of prediction, detecting anomalies, and being more efficient in the farm-to-fork continuum, IoT-facilitated sensing can offer 24/7 and high-resolution coverage of the environmental, production, and logistics states. Comparing the findings of the experiment with the conventional data-siloed systems, the predictability of agricultural production in the quantifiable manner, the reduction of post-harvest losses, logistics optimization, and compliance with food safety are determined. Besides, blockchain integration provides secure traceability and information and data sharing as well as recording that cannot be modified thereby improving consumer and stakeholder trust. The net effects of these technologies have been massive improvements in the aspect of sustainability and risk reduction besides the high efficiency of operations as demonstrated in the tabular and graphical results. The applicability of the proposed framework to the

real agri-food situation is demonstrated by better traceability completeness, waste reduction, and quicker responses to the threat of contamination. More importantly, the system is resilient and scalable in case of simulated stress situations which mean that it will be applicable to both large, global supply chains and small-scale agriculture enterprises. Simultaneously, according to the overall results of the research, the AI, IoT and blockchain together can be viewed in terms of a comprehensive data-based premise of the Food Industry 4.0 since it will enable the proactive control, greater transparency, and enhanced food safety results. The given plan is a possible way to strong and stable agri-food systems and consumer trusted systems. It also allows forming the base of a strong technological base of further advances of smart agriculture and digital supply chain management.

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