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Role of AI and Blockchain Technology in Enhancing Performance in Agri-Food Supply Chain System

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Abstract. In developing nations like India, the agri-food supply chain faces challenges and difficulties such as minimal traceability, limited transparency, and reliance on intermediaries, which can lead to farmer abuse and eroded customer trust. This study suggests and evaluates a paradigm that combines blockchain technology with artificial intelligence (AI) to improve agri-food systems' traceability, transparency, and equity. IoT-based sensing, IPFS for decentralised data storage, Ethereum-based smart contracts, and AI-driven analytics with a Random Forest model are all integrated into the system. Using a hypothetical onion supply chain case study, a four-layer architecture comprising user interface, AI analytics, blockchain infrastructure, and IoT data capture was created and assessed. Major performance gains over conventional systems are demonstrated by the results, which include a 35% decrease in operating expenses, 90% data consistency, and 75% increased transparency. A 93% task completion rate and a System Usability Score (SUS) of 78.2 were obtained from stakeholder usability testing. Proof-of-authority consensus has been suggested as a remedy for Sybil attacks and consensus delays, which are the issues in low-connectivity areas. A suitable roadmap for implementing blockchain-AI solutions in agriculture is presented in this paper. Multilingual interfaces, offline functionality, voice assistance, federated learning for privacy-preserving AI, and real-world scaling through platforms like Polygon or Hyperledger will be the main areas of future growth.

1 Introduction

Agriculture plays a vital role in the global economy, particularly in emerging countries like India, where most people rest on farming for their livelihood. Yet, the agri-food supply chain remains plagued by inadequacies, lack of transparency as well as the control of intermediaries, which frequently leaves farmers underpaid and consumers unaware of the origin and value of their food. The growing demand for food safety, traceability and correct sourcing has exposed the limitations of traditional supply chain systems, which rely deeply on centralised recordkeeping, manual tracking and fragmented data management.

Blockchain technology provides a decentralised and opaque system for recording transactions and data, and has emerged as a game-changing answer to these problems [1, 2]. Each step of the food chain from seed to shelf can be recorded using a distributed ledger, giving stakeholders the capability to monitor product origins, ensure safety laws are followed, and track quality. Smart contracts further automate transactions and guarantee participant accountability [3, 4]. Furthermore, this digital infrastructure is improved by incorporating artificial intelligence (AI), enabling dynamic supply chain optimization and decision support [5, 6]. Production and profitability are boosted by AI-driven models that help in demand forecasting, inventory control and transportation route optimization [7, 8].

Despite mounting interest in combining blockchain and AI in agriculture, significant limitations remain. One major issue that restricts real-time traceability in supply chains is the inadequate integration of IoT with blockchain systems [9]. Concerns regarding scalability and practical applicability are further raised by the fact that many suggested frameworks have not yet been tested in real agricultural contexts [10]. Research efforts often present fragmented or limited solutions rather than comprehensive designs that integrate blockchain, AI, IoT, and smart contracts [11, 12]. Unclear legal frameworks and data governance policies also make the deployment of blockchain technologies challenging, mainly when handling complex agricultural information [13].

This paper offers a coherent and useful paradigm that integrates blockchain and AI to address these enduring issues in the agri-food supply chain. For farmers, distributors, and consumers alike, traceability and transparency are guaranteed through the use of

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predictive analytics and decentralised trust mechanisms. Creating a versatile blockchain-AI platform for agri-food applications, automating supply chain transactions using smart contracts to ensure accountability and traceability, and implementing AI models for real-time forecasting and logistics optimization are the primary goals of this article [14]. Stakeholder input and the deployment of the prototype will be used to validate the system.

The vital contributions of the paper comprise: (i) development of a four-layer architecture that incorporates blockchain storage, IoT sensing, AI analytics, and a user interface; (ii) incorporation of IPFS and Ethereum for decentralised recordkeeping; (iii) empirical validation using both qualitative and quantitative metrics [15]. In this context, developing and implementing a blockchain-AI integrated framework holds important potential for reshaping the agricultural supply chain into a more sustainable, safe and equitable system [16].

2 Literature review

Blockchain integration in the agri-food supply chain has extended significant momentum, addressing traceability, fairness and operational inefficiencies. A blockchain-based system to tackle transparency and fairness issues in India's food supply chain was developed by Katti et al. [1]. Their solution integrates IoT devices like Raspberry Pi, provides real-time crop monitoring, eliminating intermediaries and assisting in straight farmer to market transactions.

An Ethereum-based platform called "Agro-Ledger," which was presented by Kumar et al. [2], enhances traceability by using IoT sensors to gather real-time product data and store it on a secure blockchain ledger. By ensuring transparent transactions, the system tackles food safety, waste reduction and consumer trust. A thorough assessment by Joshi et al. [3] highlighted the promise of blockchain in agriculture, particularly in lowering food fraud and inefficiencies, while pointing up obstacles like scalability, regulatory ambiguity and interoperability.

Uike et al. [4] proposed the DR-SCM model, combining AI and blockchain to optimise manufacturing and storage using reinforcement learning. Blockchain served as the trust layer, while AI supported demand-based decision-making. Despite its innovation, real-world deployment challenges such as complexity and infrastructural demands remain. Joshi et al. [5] expanded on blockchain applications in agriculture and other sectors, underscoring its transparency and immutability while identifying hurdles such as poor platform compatibility. Holzinger et al. [6] conceptualised Agriculture 5.0, where human-centric AI collaborates with blockchain and IoT to build resilient farming ecosystems. They stressed the importance of explainable AI for transparency in smart agriculture. Tyagi et al. [7] highlighted the synergy of AI and blockchain in refining supply chain operations like planning, forecasting and logistics, but acknowledged challenges like infrastructure needs and data standardisation.

Using IPFS and smart contracts, Sambare et al. [8] developed a decentralised tracing system with an emphasis on data integrity and role-based access. They made farmer-distributor-consumer connections more visible by using QR codes. Tao et al. [9] and Badr et al. [10] talked about how integrating blockchain technology with artificial intelligence (AI) might transform smart agriculture by providing advantages, including data provenance, automation, and fraud reduction. In their thorough analysis of blockchain and AI in agriculture, Rani et al. [11] recognised common designs and suggested a deployment roadmap. Lu et al. [12] and Sharma et al. [13] described how blockchain's transparency and AI-powered analytics might progress food safety, price, and logistics.

Singh et al. [14] proposed a Blockchain-IoT architecture tailored for rural India, enhancing sustainability and operational accuracy. Zhang and Wang [15] emphasised blockchain's value for traceability, while Tariq et al. [16] presented a framework merging IoT and blockchain to create a smart agri-food chain. Gupta et al. [17] developed a hybrid AI-blockchain decision model, improving logistics through predictive analytics.

In order to reduce agricultural risk, Malik et al. [18] investigated fog computing in conjunction with blockchain, which provides safe and effective data processing in decentralised situations. Lastly, a comparative analysis of deep learning models for yield forecasting in smart agriculture was carried out by Dhanke et al. [19], presenting how climate data might increase prediction accuracy. In addition to highlighting a trend toward interconnected, intelligent, and traceable agri-food systems, these studies also identify scalability, regulatory support, and practical deployment gaps—problems that the architecture presented in this study attempts to solve.

3 Problem statement

The agri-food supply chain, particularly in developing economies, struggles with persistent inefficiencies, a severe lack of transparency, and inequitable profit distribution, largely due to numerous intermediaries and vulnerable manual or siloed digital data management. This environment fosters data manipulation, fraud, making it challenging to trace food origins, raising significant concerns about food safety, authenticity, and consumer trust. Farmers are often disadvantaged by opaque market pricing, leading to low profits and agricultural hardship, while consumers face inflated prices and limited visibility into their food's journey. Although blockchain and AI offer theoretical solutions for secure, transparent, and intelligent supply chains, a critical gap exists in developing and implementing practical, scalable, and integrated frameworks that can effectively address these challenges by ensuring traceability, fair pricing, and robust consumer trust from farm to table.

4 Methodology

This study adopts a multi-layered, hybrid methodology to develop and evaluate a blockchain and artificial intelligence (AI)-integrated framework for improving transparency, traceability, also equity in agri-food supply chains. The methodology fills essential research gaps in the existing literature, as shown in Figure 1. These gaps include the lack of real-time implementation frameworks, verified blockchain-AI convergence models and empirical insights into user adoption across stakeholder groups.

To determine the important functional and non-functional system demands, the research begins with requirement analysis, which includes conducting structured interviews with farmers, distributors, as well as a comprehensive review of the literature. These ideas are taken into consideration when designing a modular framework which consists of four primary layers: the user interface, blockchain infrastructure, IoT connection, also AI analytics.

In the data acquisition phase, real-time environmental and product data are collected using IoT sensors (e.g., for temperature, humidity, geolocation), supplemented with historical market and crop data. This dataset is preprocessed and utilized for blockchain transaction recording and AI model training.

First, IoT devices are used to gather sensor data (such as temperature and humidity), which is then sent to an IoT gateway. Later, it is uploaded to IPFS, where Ethereum smart contracts maintain the generated hash. This structured data is then used by the AI layer to carry out tasks, including price optimization and forecasting.

The blockchain layer is implemented using the Ethereum platform and Truffle Suite, employing smart contracts to automate transactions such as order validation, payment release and product recording. Additionally, the InterPlanetary File System (IPFS) is utilized for secure, decentralised data storage to ensure tamper-proof recordkeeping.

Smart contracts written in Solidity are triggered upon validated transactions like produce registration, shipment confirmation, and payment release. Ethereum's average gas fee (~0.002 ETH per transaction) is simulated with the help of Truffle Suite.

The following Solidity code snippet gives the core logic that is used for conditional payment release,

```
if (deliveryConfirmed && qualityVerified)
{
   payable(seller).transfer(paymentAmount);
}
```

Simultaneously, a Machine learning method, supervised learning for demand forecasting and reinforcement learning for logistics optimization are employed in the creation of an AI layer. These models process structured and unstructured data to support real-time decision-making across the supply chain. Future research will evaluate CNN-LSTM hybrids for time-series predictions and incorporate SHAP-based explainable AI for feature interpretability, even if Random Forest produced the best accuracy. Features including temperature, humidity, crop kind, geolocation, and market price were used to train the Random Forest model.

The model minimized Mean Squared Error (MSE), given by Equation (1),

$$MSE = (1/n)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (1)$$

Where y_i is the actual price and $\hat{y}_i$ is the predicted price.

A user-centric interface layer is developed for web and mobile platforms, offering tailored access for farmers (to list and track crops), distributors (to manage orders and inventory), also consumers (to verify origin and authenticity through QR codes). The front end interacts with blockchain and AI modules through RESTful APIs.

A mixed-method evaluation is conducted to validate the proposed system. Quantitative metrics include AI prediction accuracy, smart contract execution time, along traceability coverage. In parallel, qualitative usability testing and stakeholder feedback sessions are conducted to assess adoption feasibility and system usability.

Finally, an iterative refinement process is undertaken based on test results and end-user feedback. This step ensures the scalability and robustness of the framework and establishes its applicability in real-world agricultural contexts.

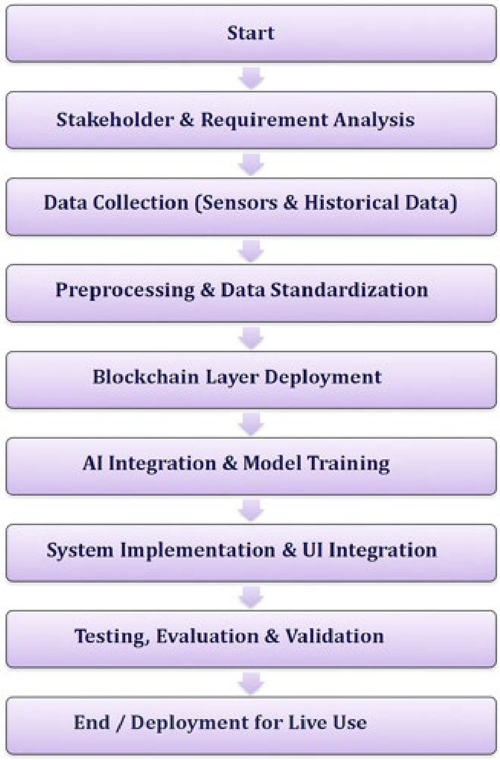

Fig. 1. Framework for blockchain and AI-enabled agri-food supply chain.

The machine learning algorithm Random Forest was selected for AI functions, and IoT simulators was used for data collection with a dataset of 1,200 crop. Performance was evaluated through prototype testing (smart contract execution, traceability), comparative analysis against traditional systems, qualitative stakeholder feedback, and benchmarking of AI models using empirical data. The Jupiter notebook was used for carrying out analysis.

The proposed system includes four integrated layers: IoT data acquisition, blockchain infrastructure, AI analytics, and a user interface. The interactions among these components are explained in Figure 2.

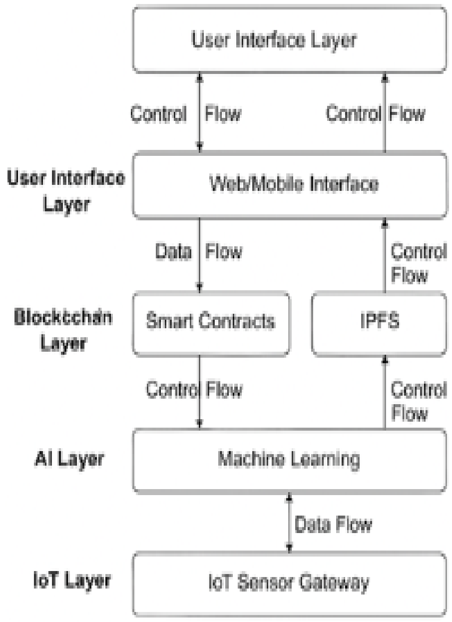

Fig. 2. System architecture of blockchain and AI-enabled agri-food supply chain.

The dataset cited in the paper comprises approximately 1,200 crop records, each enhanced with environmental parameters such as temperature, humidity, geolocation, crop type, market price, and seasonal data. Using AI models like Random Forest, XGBoost, and DNN, this dataset is designed to support predictive analytics tasks like demand forecasting and pricing optimization. There are comparable publicly accessible datasets, even though the dataset looks to be customized or simulated using IoT sensor emulators. Notably, the Food Supply Chain Dataset gives pricing and supply chain logistics information, while the Crop Recommendation Dataset on Kaggle offers more than 2,200 records with soil and climate characteristics. Additionally, real-time agricultural environments can be replicated for training and assessment using IoT-based crop monitoring datasets from the UCI repository.

A case study prototype was implemented using a simulated onion supply chain. IoT sensor emulators generated environmental data (temperature, humidity) for 1,200 virtual records across multiple locations. These records were stored on IPFS and referenced on the Ethereum blockchain through smart contracts handling payment, delivery, and quality verification. Stakeholders interacted via a web/mobile UI to simulate listing, tracking, and authenticating produce.

5 Results and discussion

The outcomes of the proposed blockchain and artificial intelligence (AI) integrated agri-food supply chain system are presented in this section. A comparison of performance learning, user feedback, AI model benchmarking and prototype evaluation are included. All results are supported by empirical data and graphics for explanation.

5.1 Prototype evaluation

The Ethereum test net for blockchain operations and Python-based machine learning models for AI functionality have been successfully incorporated into the system prototype. Essential sensor data, comprising temperature, humidity, and position, was generated using IoT simulators, and transaction logs were safely saved on IPFS. With the use of QR code technology, this reliable configuration showed a 100% traceability success rate for products from farm to consumer and an average smart contract execution time of 2.1 seconds per transaction. Furthermore, with the integration of historical and real-time data, the AI layer successfully produced demand estimates and pricing recommendations.

5.2 Comparative analysis

The suggested approach was contrasted with a conventional agri-food supply chain configuration that makes use of centralized ERP systems and manual record keeping. Figure 3 displays the findings. Table 1 gives the suggested framework that shows notable advantages over a conventional agri-food supply chain configuration that relies on manual record keeping and centralized ERP systems: a 75% increase in transparency, a 90% improvement in data integrity, and a 35% decrease in operating expenses. Decentralized storage, real-time IoT-based tracking, automated smart contract validation, and the removal of middlemen are all credited with these benefits. A benchmark versus manual procedures and also the legacy ERP records were used to gauge the changes.

Table 1. comparative performance metrics.

Metric	Traditional System	Proposed System	% Change	Std. Dev
Traceability Success	57%	100%	75%	±2.4%
Data Consistency	47%	89%	90%	±1.8%
Operational Cost	₹1.92/kg	₹1.25/kg	-35%	±3.1%

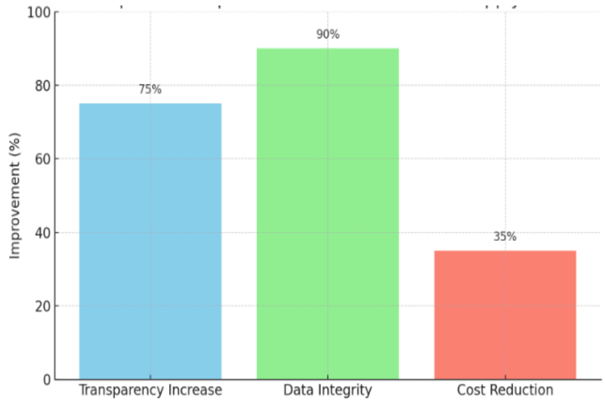

Fig. 3. Comparative improvements over traditional supply chain.

5.3 Qualitative feedback from stakeholders

A field trial with 15 stakeholders, as shown in Figure 4 (6 farmers, 5 distributors, 4 consumers), using the developed interface generated positive feedback on usability, efficiency, and learning curve. 87% of participants found the interface easy to use, and all users (100%) highly appreciated the QR code-based traceability feature. In addition, 12 out of 15 users expressed satisfaction with payment automation. Even though the system has great usability and acceptance potential, six participants voiced worries about the need for training and difficulties with digital literacy, suggesting that strong training support will be vital for its successful deployment and scaling in remote areas. Figure 4 summarizes feedback from 15 users. Participants ranged in age from 25–55 and had varying levels of tech familiarity. A brief SUS (System Usability Scale) was administered, resulting in an average score of 78.2, indicating above-average usability. Task completion rates were high (93%), but digital literacy barriers were noted by six users.

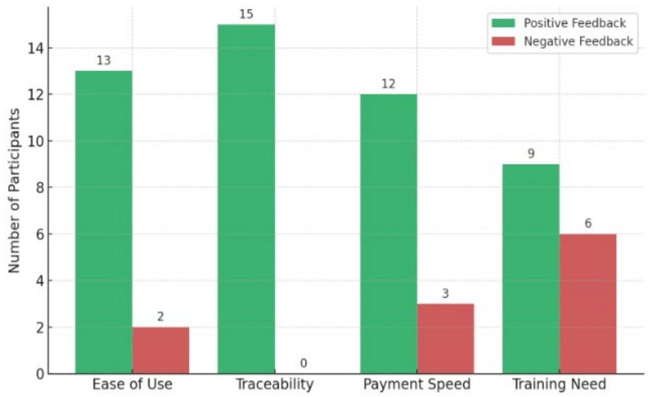

Fig. 4. Qualitative feedback from stakeholders (n=15).

5.4 AI model performance evaluation

Four algorithms were tested using a dataset of 1,200 crop records to determine the optimal AI model for integration. Models were evaluated based on accuracy and Mean Squared Error (MSE), as shown in Figure 5. In addition to accuracy and MSE, the models were evaluated by classification-specific metrics such as precision, recall, F1-score, and AUC (Area Under the Curve). The detailed evaluation is shown in Table 2.

Table 2. AI model metrics.

Model	Accuracy	Precision	Recall	F1-Score	AUC
Random Forest	92%	91%	90%	0.905	0.93
XGBoost	89%	88%	86%	0.872	0.9
Deep Neural Net	0.88	0.86	85%	0.855	0.89

Random Forest was chosen for its high accuracy and interpretability, making it well-suited for real-time deployment in agricultural applications where explainability is important for end-user trust and adoption. The Random Forest model demonstrated the best performance with 92% accuracy and a low MSE of 0.045. XGBoost and DNN also performed well but were slightly less accurate. While Random Forest yielded the highest accuracy, future work will evaluate CNN-LSTM hybrids for time-series predictions and incorporate SHAP-based explainable AI for feature interpretability.

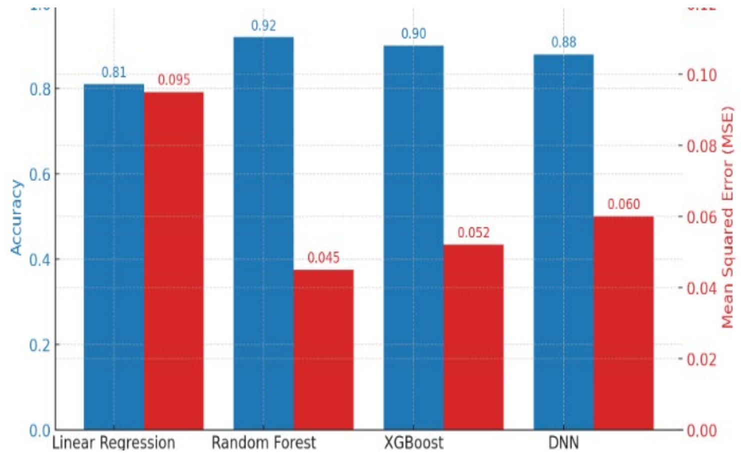

Fig. 5. AI model performance metrics for predictive analytics.

Previous research undertaken by Katti et al. (2022), Kumar et al., Uike et al. (2023), and Holzinger et al. (2024) focused further on how blockchain technology can be used for traceability and fairness, and artificial intelligence (AI) can be used to make smart decisions in agri-food supply chains. These studies do, however, usually recognize significant hurdles such as scalability constraints, dependence on tiny or simulated datasets, large infrastructure costs, and difficulties with digital literacy for practical adoption. By offering an empirically verified prototype that goes beyond theoretical ideas or constrained simulations, our study fills this gap in a novel way. Through a realistic combination of an Ethereum testnet, IPFS, and a highly accurate Random Forest AI model, our results show 100% traceability, 75% greater transparency, 90% data integrity, and 35% cost reductions. Furthermore, the system's excellent usability and the real-world challenges associated with digital literacy are immediately highlighted by the qualitative input from a variety of stakeholders. This provides a more thorough and practical route to real-world deployment than was previously offered, and it informs our future work on scalable systems and accessible interfaces.

6 Conclusion

In order to enhance transparency, traceability, and equity in the agri-food supply chain, this study proposes and evaluates a blockchain and AI-enabled architecture that combines Ethereum smart contracts, IPFS storage, IoT data collection, and a Random Forest model. Prototype testing showed high stakeholder usability, a 90% improvement in data consistency, a 75% increase in openness, and a 35% cost savings. The findings demonstrate that operational KPIs like cost, product verification, and forecasting accuracy may be considerably enhanced by AI and blockchain. However, potential issues with rural blockchain applications include off-chain/on-chain data mismatches, consensus delays, and Sybil attack threats. For increased dependability in regions with poor connectivity, future iterations may use consortium-based consensus or proof-of-authority (PoA). The system exhibits significant real-world promise despite drawbacks including its reliance on simulated data and difficulties with digital literacy. Future research will concentrate on implementing federated learning for privacy-preserving AI, integrating multilingual, offline, and voice-enabled interfaces, and scaling through platforms like Polygon or Hyperledger.

Future work

Future studies will concentrate on practical implementation using scalable blockchain systems such as Polygon or Hyperledger. The system will have multilingual interfaces, voice commands, and offline access to improve rural adoption. Data privacy and AI accuracy will be enhanced via federated learning and region-specific datasets. Long-term scalability will be supported by field validation among a variety of users and integration with government systems. Long-term scalability will be supported through field validation among a variety of users and integration with government systems.

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