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Blockchain based Agri food Supply chain using AI Smart Contracts

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Abstract:- Blockchain technology offers a revolutionary way to improve the agricultural food supply chain's traceability, security, and transparency. As global food production and consumption continue to increase, systems that can efficiently track and verify food products from farm to table are becoming more and more important. Food safety and quality are a concern because current supply chain models frequently have problems with data integrity, fraud, and transparency. This paper proposes a comprehensive framework that incorporates a multi-layer architecture, including a data layer, blockchain layer, AI layer, traceability chain, and off-chain databases, to address these problems. The data layer collects and processes relevant data from all stakeholders in the agricultural supply chain to guarantee accurate and consistent data flow.Trade and delivery events are permanently and explicitly recorded by the blockchain layer, which uses smart contracts to automate transactions and enforce adherence to predefined standards.The suggested method improves data security and privacy by combining Artificial Intelligence (AI) with Multi-Party Computation (MPC) to give intelligent, privacy-preserving analytics.This link allows for collaborative verification and forecast findings without revealing personal participant information.Additionally, a Trusted Execution Environment (TEE) ensures tamper-proof operations by securely isolating critical calculations behind a hardware enclave. Participants may confirm that all data stored or off-chain is genuine and unaltered because of hash functions, which also offer data immutability and integrity. The proposed blockchain-based smart contract solution works effectively with transaction quantities between 25,000 and 28,500 Gwei across various Agri-Food Supply Chain operations. The average transaction time, which ranges from 0.001 to 0.0025 ms, demonstrates low latency and excellent responsiveness.

Keywords*: Blockchain , Multiparty Computation , Smart contracts, Traceability, Trusted Execution Environments*

1. Introduction

The worldwide agri-food industry is going through a significant digital change as a result of the growing demands for efficiency, safety, and transparency. Global food production is expected to surpass 380 million metric tonnes by 2028, according to FAO (2024), and the agri-food supply chain sector is expected to increase at a rate of 7.2% annually to reach USD 340 billion by 2032 [1]. Food poisoning, data manipulation, and lack of traceability continue to be significant issues that jeopardise customer confidence and sustainability notwithstanding these developments [2]. Human health is still negatively impacted by the excessive use of growth hormones, fertilisers, and pesticides, which emphasises the need for data-driven, intelligent, and secure food management systems.

Global food security, economic stability, and consumer health are all dependent on the agricultural food supply chain (AFSC). From agricultural production to manufacturing, processing, distribution, and retailing, it passes through several interconnected processes before it is consumed [3]. As the world's food production continues to rise, the complexity of these interconnected systems has greatly increased, making it difficult to monitor, verify, and ensure transparency throughout the whole supply chain. Traditional centralised systems are vulnerable to fraud, counterfeit goods, data manipulation, and poor participant coordination because they often lack end-to-end traceability [4]. By jeopardising food sustainability, safety, and quality, these problems highlight the necessity of an innovative, transparent, and secure supply chain architecture.

In addition to financial losses, issues with the conventional food supply chain lead to food waste, health risks, and consumer mistrust. As a distributed, indestructible digital database that precisely and openly records every event or transaction along the food supply chain, blockchain offers an enticing option in this field [5].

Concerns about fair trade, sustainability, climate change, and food safety have made modernising agricultural value chains even more important. Government regulations, consumer awareness, and international trade agreements all have an impact on the significance of digital traceability and data transparency [6]. Agriculture is going through a technological revolution because of programs like India's National Agriculture Market (eNAM) and the European Union's Farm to Fork Strategy.

One potential way to overcome these constraints is to combine Multi-Party Computation (MPC) and Artificial Intelligence.While MPC guarantees data privacy and safe computation across numerous parties without disclosing sensitive information, AI allows real-time decision-making, anomaly detection, and predictive analytics throughout the supply chain [7]. A key component of contemporary food traceability is the cooperative examination of shared statistics by stakeholders, such as farmers, distributors, and regulators.

When combined with blockchain technology, these AI-MPC systems offer complete transparency, immutability, and trust for agri-food transactions (BCT).Through automated decision-making and computation that protects privacy, AI and MPC improve the intelligence and security of trade, logistics, and compliance data maintained in a tamper-proof ledger via blockchain.When combined, these technologies provide a reliable, decentralised platform that ensures food authenticity and quality while promoting sustainable growth in international agri-food networks [8].

The key contribution of proposed method is,

• AI-enhanced MPC is used by the framework to enable secure, collaborative analysis of private supply chain data.

• End-to-end traceability of agri-food products and transparent, immutable transaction records are guaranteed by blockchain with smart contracts.

• Trusted Execution Environments (TEE) and hash-based approaches provide tamper-proof security, ensuring data integrity and critical operations.

By integrating these cutting-edge technologies, the suggested approach provides a reliable way for contemporary agri-food supply chains to deal with the crucial problems of security, transparency, and trust. The concept shows how integrating blockchain and AI could revolutionise supply chain management, guaranteeing robustness, dependability, and accountability while promoting informed decision-making and protecting stakeholder interests [9].

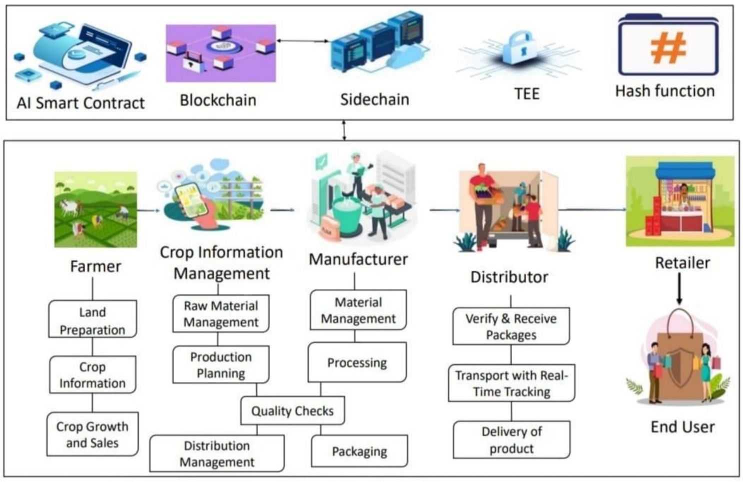

Fig 1: Proposed blockchain based agrifood supply chain.

An example of a blockchain-based supply chain system that integrates AI Smart Contracts, Sidechains, and Trusted Execution Environments (TEE) for efficiency and security is shown in this figure. It describes the product's path from the farmer (crop growth, land preparation), to the manufacturer (processing, quality control), to the distributor (distribution, tracking), and lastly to the retailer and end user. Providing visible, traceable, and secure management of the product and its data at every stage—from raw materials to customer purchase—is the main goal.

Literature Survey:

To solve enduring issues in supply chain systems, new technologies like blockchain, IoT, and AI have been thoroughly investigated in recent years. Issues including data manipulation, traceability, transparency, and inefficiency at different levels are common in traditional supply chains. Because of this, academics have been concentrating more on combining secure and decentralized technologies to provide automation, trust, and real-time visibility in multi- stakeholder settings. This section examines significant research that has influenced this changing field of study.

Siddiqui et al. [10] highlighted the potential of integrating blockchain and IoT in smart agriculture and food supply chains, enabling real-time monitoring, secure data recording, and automated processes through smart contracts. Despite reducing administrative overhead and improving transaction efficiency, challenges such as interoperability issues, security risks, and high initial costs were noted.

Building on this, Peng et al. [11] proposed the MBRRSM framework for the rice supply chain, combining multi-party authentication, secure multi-party computation, and a "main chain + sub-chain + cloud" storage model to enhance data security and efficiency. While effective in record control, the framework faced limitations in handling manually entered data and scaling to other crops.

Iftekhar et al. [12] applied Hyperledger Fabric to trace food packages from farm to fork, promoting quality competition among enterprises. Their approach highlighted blockchain's potential in existing enterprise environments but faced challenges in seamless system integration and workforce adaptation. Similarly, Khan et al.[13] combined metaheuristic algorithms and blockchain for agricultural commodity price forecasting, addressing real-time monitoring and decentralized data management, yet encountering complexity in system integration and transaction execution.

Treiblmaier et al. [14] examined blockchain's role in enhancing consumer trust through traceability, showing its impact on perceived product value and purchase behaviour, though long-term effects across different food categories remained underexplored. Rejeb et al. [15] emphasized blockchain's capacity to improve supply chain collaboration, accountability, and transparency, while noting persistent vulnerabilities and the need for complementary technologies. Latif et al. [16] demonstrated blockchain's efficacy in asset tracking and transaction validation using SKU-based product entries, with strong security benefits but remaining challenges in scalability and network reliability.

Collectively, these studies illustrate the promise of blockchain and related technologies in enhancing transparency, security, and efficiency in agri-food supply chains, while also highlighting existing limitations that motivate further research in secure, multi-layered, and AI-enhanced supply chain frameworks.

2. Objectives

The proposed strategy aims to enhance security, trust, and transparency across the agriculture supply chain by accomplishing four primary objectives. The first goal is to enable end-to-end traceability of agricultural products by using blockchain technology to document every transaction from the farmer to the consumer. Second, it ensures safe and private data flow between stakeholders by utilising smart contracts and multi-party computation (MPC) to enable private yet verifiable transactions. Thirdly, the system will incorporate AI-powered decision support for automated quality analytics, trust assessment, and validation to boost operational reliability.Finally, it protects data integrity and confidentiality by utilising decentralised, cryptographically secure storage technologies like IPFS and Trusted Execution Environment (TEE). When combined, these goals create an ecosystem for the agri-supply chain that is transparent, reliable, and guarantees everyone's trust and accountability.

3. Methods

To provide security, traceability, and transparency throughout the agricultural supply chain, the proposed method integrates blockchain technology and artificial intelligence (AI) in a multi-layered architecture. The framework is divided into four interconnected layers: the Data Layer, Blockchain Layer, AI Layer, and Storage Layer, in order to ensure complete data integrity and stakeholder confidence. Each layer has a different yet complementary purpose.

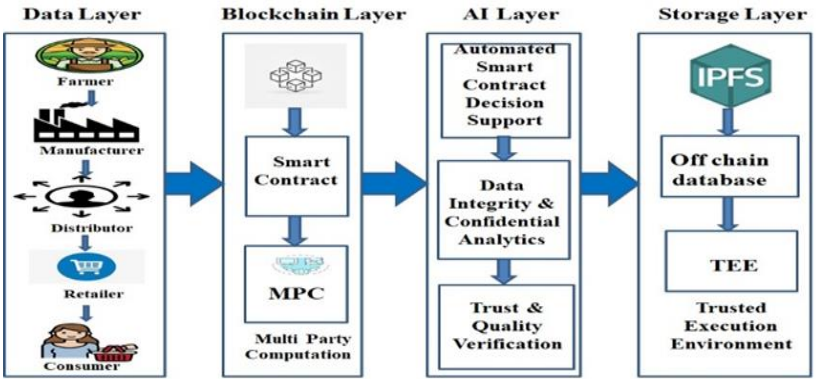

Fig 2: Layered Framework for Blockchain enabled Agri-Food Traceability.

DATA LAYER:

The system's data layer is its cornerstone, gathering information from important parties like farmers, manufacturers, distributors, retailers, and customers. Contributions of precise, time-stamped information about the production, processing, distribution, and sale of agricultural goods are the responsibility of every partner. This layer verifies inputs before they are sent to the blockchain network, guaranteeing data transparency and validity. Across the whole supply chain, the Data Layer enables smooth communication and traceability using digital IDs and standardised data formats.

Table1: Data Layer Algorithm

```
Algorithm DataLayer_Process()

  For each Entity in [Farmer, Manufacturer, Distributor, Retailer]:
     data ← CaptureData(Entity)
     encrypted_data ← Encrypt(data, Entity.PrivateKey)
     signature ← Sign(encrypted_data, Entity.PrivateKey)
     SubmitTransactionToBlockchain(encrypted_data, signature)

  EndFor
  Notify(Consumer, "Traceability data available")
EndAlgorithm
```

The Data Layer Algorithm safely gathers and logs information from all parties involved in the agricultural supply chain, including farmers, manufacturers, distributors, and retailers. To ensure authenticity and confidentiality, each entity's data is first recorded, encrypted, and then digitally signed using its private key. The encrypted data is then moved to the blockchain, where it is permanently preserved and accessible to authorised users for verification. The customer is notified that the entire traceability record is available once all parties have contributed their data. This process ensures safe, transparent, and unbreakable data sharing throughout the supply chain.

BLOCKCHAIN LAYER:

The Blockchain Layer handles safe, immutable data recording. It uses Multi-Party calculation (MPC) to protect data privacy and smart contracts to automate verification processes while permitting computation over encrypted inputs. This ensures the confidentiality of critical company information while enabling stakeholders to mutually validate data. The supply chain network establishes end-to-end traceability and accountability by immutably storing all transactions on the blockchain, including factory updates, shipment information, and quality checks.

Table2: Blockchain Layer Algorithm

```
Algorithm Blockchain_TransactionValidation()

 Input: encrypted_data, signature

  If VerifySignature(encrypted_data, signature) == TRUE:
     result ← ExecuteSmartContract(encrypted_data)
     secure_result ← MPC(result)
     AppendBlockToChain(Hash(secure_result))
     Return "Transaction Confirmed"

  Else
     Return "Invalid Transaction"
  EndIf
EndAlgorithm
```

The Blockchain Layer Algorithm safely logs each transaction on the blockchain after confirming its legitimacy. After confirming the digital signature, a smart contract completes the transaction; privacy processing is handled by Multi-Party Computation (MPC). The output is hashed and uploaded to the blockchain following verification. When verification fails, transactions are refused. This ensures immutable, transparent, and secure validation.

AI LAYER:

The AI Layer improves the blockchain architecture by offering methods for assessing trust and coming to wise judgements. Blockchain data is analysed by artificial intelligence (AI) systems to find abnormalities, confirm the product's quality, and anticipate any production or logistical problems. Using data-driven insights and predetermined criteria, the Automated Smart Contract Decision Support module facilitates the execution of dynamic contracts.Additionally, the Data Integrity and Confidential Analytics modules ensure that decision-making is based solely on trustworthy and superior data. This AI integration fosters a supply chain ecosystem that is adaptable, dependable, and efficient.

Table3: AI Layer Algorithm

```
Algorithm AI_Layer_Processing()

  Input: BlockchainData, OffChainData

  merged_data ← Merge(BlockchainData, OffChainData)
  prediction ← AI_Model.DecisionSupport(merged_data)
  integrity_score ← ComputeDataIntegrity(merged_data)
  trust_index ← EvaluateTrustQuality(prediction, integrity_score)
  If trust_index ≥ Threshold:
     ApproveSmartContractExecution()
  Else

     TriggerManualReview()
  EndIf
EndAlgorithm
```

On-chain and off-chain data are integrated by the AI Layer Algorithm to facilitate intelligent decision-making. An AI decision-support model is utilised to make predictions after first combining the two datasets. A data integrity score is used to evaluate reliability, while the prediction and integrity measures are utilised to generate a trust index. The smart contract runs automatically unless the trust index falls below a predetermined threshold, in which case a manual review is started. The supply chain's automated, data-driven, and reliable contract execution is guaranteed by this procedure.

STORAGE LAYER:

Scalability and confidentiality are guaranteed by the decentralised, secure data storage provided by the Storage Layer. It incorporates the Inter Planetary File System (IPFS) to offer immutability and resilience against data loss in the dispersed storage of large datasets. A Trusted Execution Environment (TEE) enables secure private processing and verification, while an off-chain database manages enormous amounts of data that might not fit directly on the blockchain. When combined, these elements offer data integrity, security, and speedy retrieval, guaranteeing that every supply chain record is safe from unwanted access and verifiable.

Table4: Storage Layer Algorithm

```
Algorithm StorageLayer_Management()

  Input: VerifiedData

  hash ← GenerateHash(VerifiedData)
  ipfs_link ← UploadToIPFS(VerifiedData)
  StoreReferenceOnBlockchain(hash, ipfs_link)
  ExecuteWithinTEE(AccessControlRules)

  Return ipfs_link
EndAlgorithm
```

The Storage Layer Algorithm ensures secure and decentralized data storage. Before uploading the verified material to IPFS and obtaining a unique content identification (IPFS link), it generates a cryptographic hash of the data to maintain integrity. The blockchain stores the hash and IPFS reference for traceability and immutability. Last but not least, the Trusted Execution Environment (TEE) enforces secure data processing and access control. This process guarantees tamper-resistant, verifiable, and private storage within the supply chain network.

In conclusion, a thorough and safe framework for controlling the agricultural supply chain is produced by combining the Data, Blockchain, AI, and Storage Layers. To maintain data integrity, transparency, and stakeholder confidence, each layer has a different but related function. Automation, privacy, and process reliability are enhanced by the application of AI, MPC, and cryptographic approaches. When everything is taken into account, this tiered architecture creates a robust, perceptive, and impermeable environment for the traceability of the whole agri-supply chain.

4. Results

An innovative method for improving security and transparency in agricultural food supply chains is provided by blockchain technology. Every transaction, from manufacturing to consumption, is verifiable and impenetrable thanks to AI and cryptographic security, which solves problems with fraud, authenticity, and traceability. This integration creates an open ecosystem that fosters stakeholder trust, boosts resilience in food supply networks, and decreases inefficiencies. The test is conducted on a computer with an Intel Core i6, a 2.4 GHz processor, 250 GB of storage, and 6 GB of RAM.

The Python tool is used to create the system. A user-friendly graphical user interface (GUI) is part of the Supply Chain Management with Blockchain system, which links farmers, manufacturers, distributors, retailers, and consumers. It makes safe registration, login, and graphical data visualisation of supply chain transactions possible.

Fig 3:GUI for Supply chain Management using Blockchain

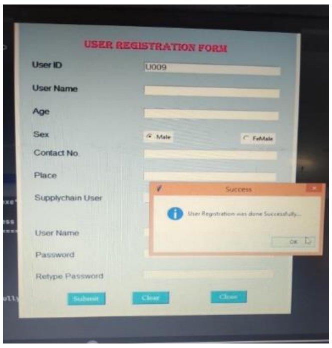

Fig 4: User Registration GUI

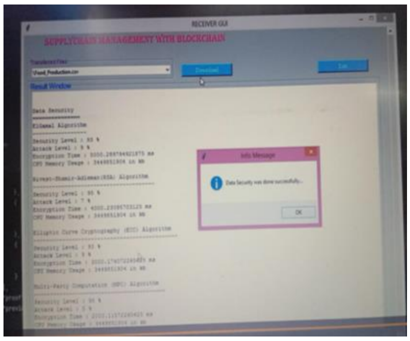

Fig 5: Receiver GUI Displaying Data Security Performance Using Cryptographic Algorithms

By offering modules for data upload, tracking, and report generation, the interface guarantees smooth communication between entities it also shows how to evaluate data security by comparing the encryption time, security level, and CPU usage of various cryptographic methods (ElGamal, RSA, ECC, and MPC). To guarantee that every transaction is securely completed before being added to the blockchain, the system notifies users when encryption is successful.

Dataset Description:

Researchers from all around the world are paying close attention to the wide applications of the agri-food supply chain (AFSC) in various industries.This study uses bibliometric techniques to analyse 303 publications from 1997 to 2021. Data is visualised using VOSviewer, and analysis is done in Microsoft Excel. According to the results, there has been a significant increase in AFSC research since 2006, with seven main subject topics being examined, such as innovations, risk, and system management. The three main areas of study—"agri-food supply chain," "food supply," and "supply chains"—indicate the expanding prospects for institutional and cross-national cooperation in this area.

➢ **Evaluation Metrics**

- Smart contract administration and transaction costs (gas),
- Total gas usage for input strings of various lengths in the review system,
- The reputation system's mining time for input strings of a variety
- The cost of smart contract implementation and
- A variety of items were registered in the Agri-Food supply chai

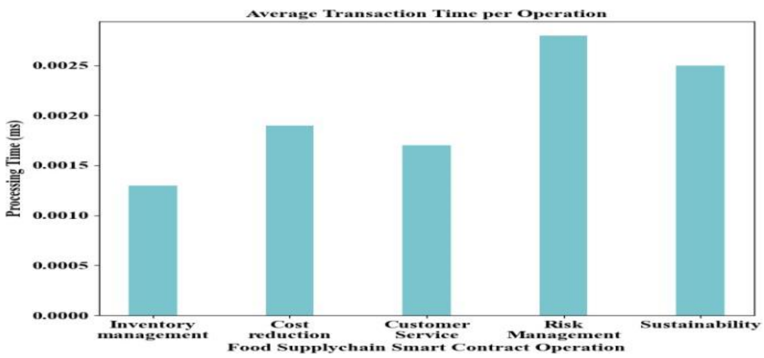

Figure 6: Average Transaction Time for Food Supply Chain Operations

Figure 6 presents the average transaction time for different operations in the AI-integrated MPC-based food supply chain. Risk Management shows the highest processing time due to the added complexity of AI analytics and secure MPC computations. Sustainability also records higher times because of integrated AI-based validation. In contrast, Inventory Management and Cost Reduction have lower processing times, indicating more efficient and streamlined execution within the proposed framework.

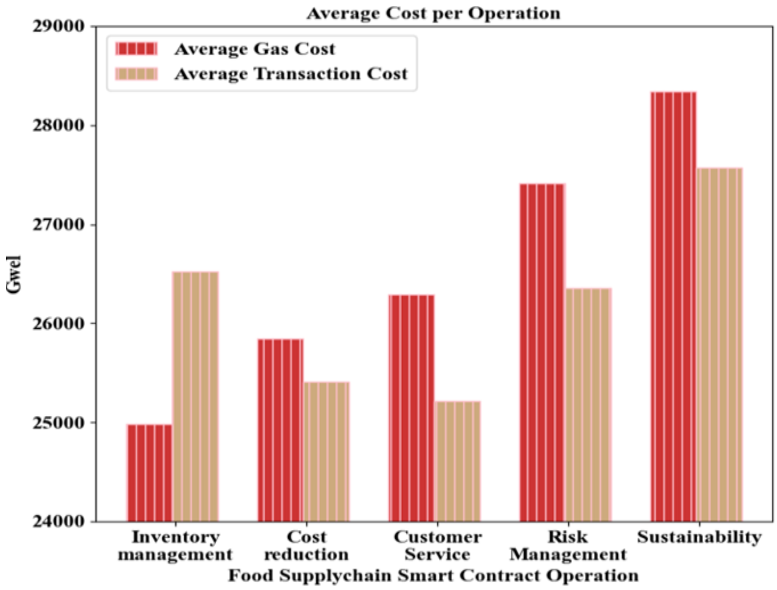

Figure 7: Average Cost per Operation in Food Supply Chain Smart Contract Operations

Figure 7 illustrates the average cost per operation in the AI-integrated MPC-based food supply chain smart contracts. Risk Management and Sustainability operations show the highest average costs due to the added computational effort from AI analytics and secure MPC protocols, which increase both gas and transaction costs. In contrast, Inventory Management and Cost Reduction have lower costs, indicating greater process efficiency. The difference between average gas cost and transaction cost provides insights into the system's economic performance, highlighting areas where AI-MPC integration can be optimized for improved cost efficiency.

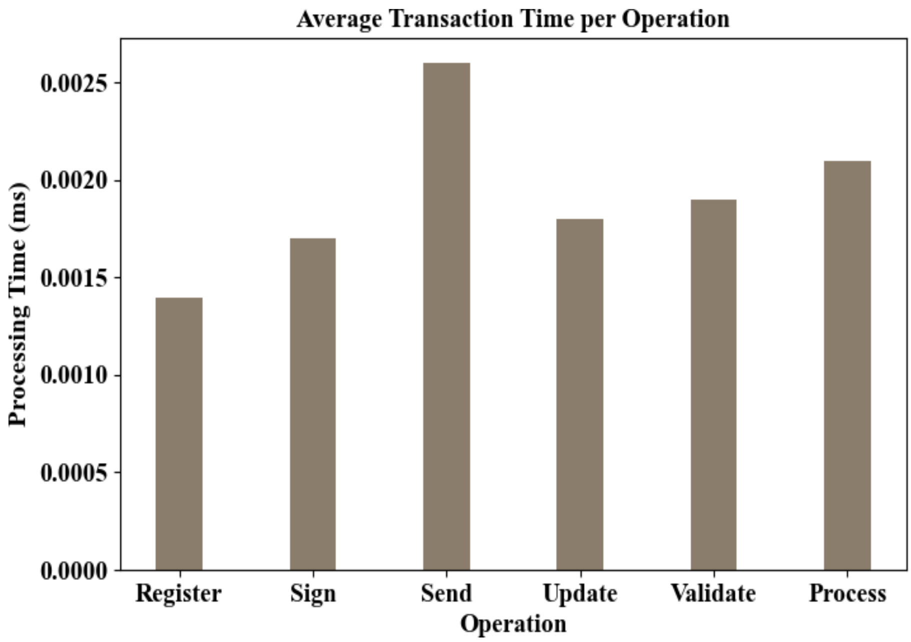

Figure 8: Average Transaction Time for Smart Contract Operations

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Figure 8 illustrates the average transaction time for various operations within the AI-integrated MPC-based smart contract framework. The Send operation demonstrates the highest processing time, likely due to the additional computational overhead from secure multiparty computation and AI-driven verification. Meanwhile, Register and Sign operations record the lowest times, indicating higher efficiency in these processes. Overall, the analysis emphasizes the need for optimization of the Send phase to improve transaction throughput and ensure smoother performance in the AI-enhanced blockchain environment.

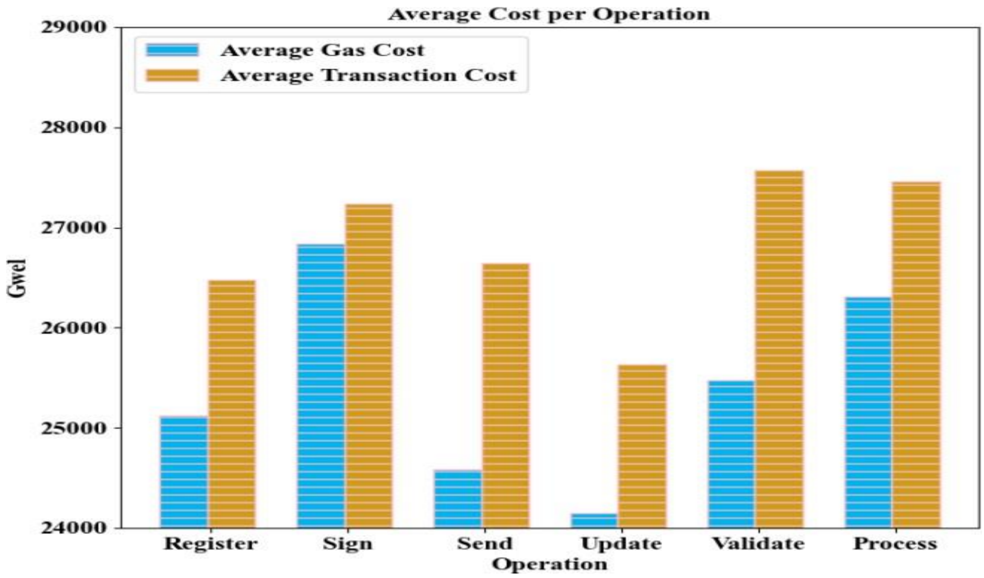

Figure 9: Average Gas and Transaction Costs per Operation in Smart Contracts

Figure 9 presents the analysis of average gas and transaction costs for different operations within the AI-integrated MPC-based smart contract system. The Sign and Validate operations show the highest costs, highlighting their computational intensity due to cryptographic verification and AI-based validation. Conversely, Register and Send operations demonstrate lower costs, indicating efficient execution. These variations underscore the importance of optimizing resource allocation and enhancing cost efficiency in AI-assisted blockchain operations.

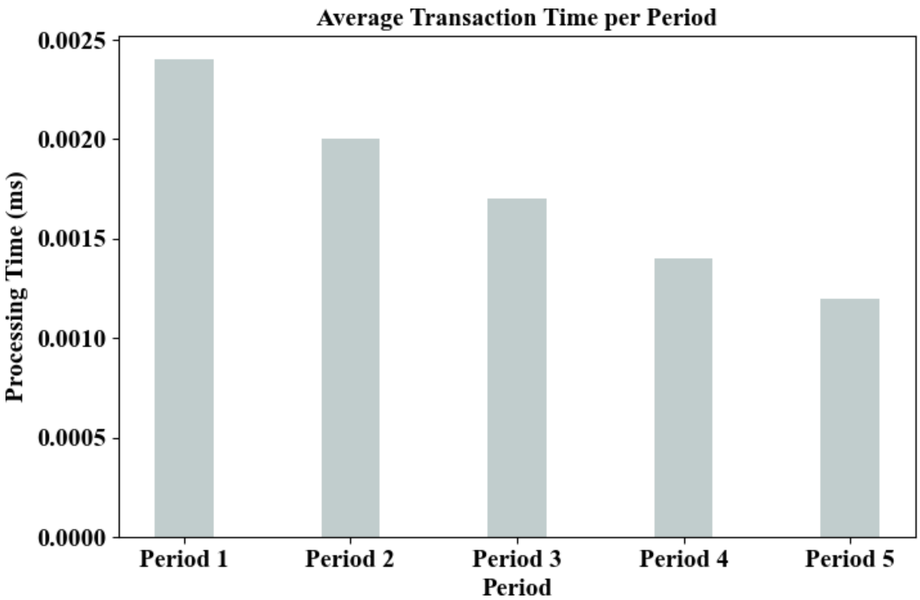

Figure 10: Average Transaction Time per Period (ms)

Figure 10 illustrates the variation in average transaction time across different periods within the AI-integrated MPC framework. Period 1 records the highest processing time, likely due to initial setup and synchronization overheads.

However, a steady decline is observed in subsequent periods, with Period 5 showing the lowest transaction time. This consistent reduction signifies enhanced system optimization, improved data handling, and adaptive learning capabilities of the AI-MPC model, leading to increased overall efficiency over time.

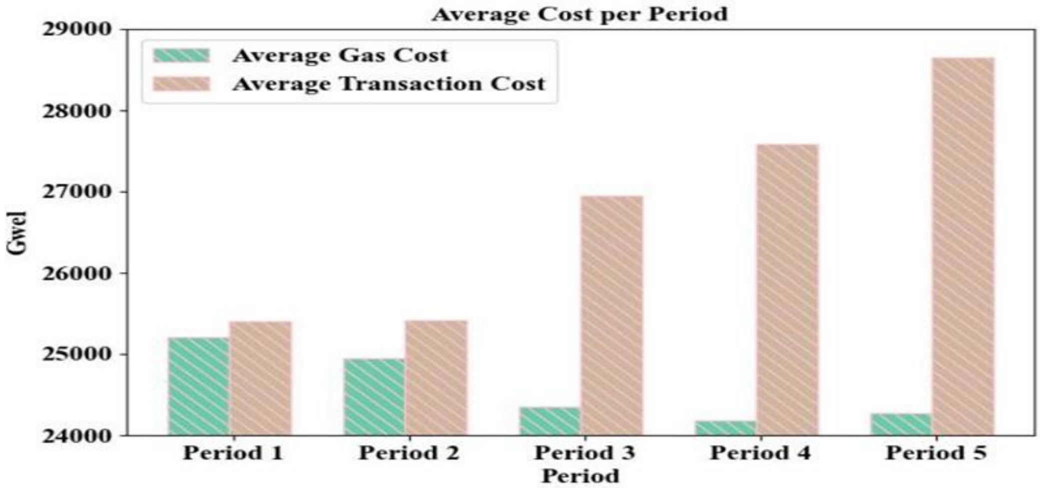

Figure 11: Average Gas and Transaction Costs per Period (Gwei)

Figure 11 illustrates the variation in average gas and transaction costs across different operational periods within the AI-integrated MPC framework. Both costs are comparatively stable during Periods 1 and 2, with petrol costs continuously being less than transaction costs, indicating early operational consistency. Transaction costs, however, peak by Period 5, suggesting increased computing demand or network congestion. This increasing tendency highlights how crucial adaptive cost optimisation techniques are for AI-MPC systems in order to preserve efficiency and avoid overusing resources in later stages of operation.These findings demonstrate significant improvements over existing methods in security and performance metrics. Comparative security analysis further illustrates the enhanced resilience and efficiency of the proposed strategy.

5. Discussions

The total research reveals significant improvements in transaction efficiency and operational transparency across the agricultural supply chain thanks to the blockchain framework and AI-enabled Multi-Party Computation (MPC). A examination of transaction time, gas cost, and processing cost over different operations and times shows that the system finally stabilises with optimal performance, despite some slight inefficiencies in the early phases. The lowering transaction time over time illustrates improved computing coordination and adaptive optimisation made achievable by AI integration. However, the observed increase in transaction and gas costs in later phases indicates an increase in computing complexity when more intricate and secure procedures are implemented. When considered collectively, these findings show how the framework may integrate data privacy, security, and scalability to offer dependable and durable supply chain management.

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