ENHANCING TRANSPARENCY AND ACCOUNTABILITY IN CORN SUPPLY CHAINS THROUGH BLOCKCHAIN AND NFT BASED TRACEABILITY: A QUANTITATIVE EXPERIMENT WITH HYPERLEDGER BESU

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Abstract: *The corn supply chain often faces problems such as low transparency, limited data sharing and lack of trust between stakeholders. This study aims to design and test a prototype of a traceability system using a permissioned blockchain (Hyperledger Besu) combined with Non-Fungible Tokens (NFT/ERC-721) to give each corn batch a unique digital identity. The research method is a quantitative experiment that measures three key indicators: throughput (transactions per second), latency (transaction speed) and resilience (system stability when a node fails). The prototype was implemented with four to five validator nodes, monitored through Prometheus and Grafana dashboards and tested using a smart contract on Remix IDE. The results show that the system can reach an average block time of 2.0 – 2.3 seconds, a throughput of 15 transactions per second and a transaction latency of about 2 seconds for minting, updating status and transferring ownership of NFTs. These findings confirm that blockchain and NFT integration can improve transparency, accountability and traceability in the corn supply chain, even though throughput is still limited by the lab environment. The study concludes that this approach is effective as a proof-of-concept for digitalizing agricultural supply chains. For future work, larger-scale testing with real supply chain data, IoT sensor integration and stakeholder participation are recommended to ensure sustainable adoption in agri-food systems.*

Keywords*: Blockchain, Corn Supply Chain, Hyperledger Besu, NFT, Quantitative Experiment*

Abstrak: *Rantai pasok jagung di Indonesia masih menghadapi tantangan berupa keterbatasan transparansi, kesenjangan informasi dan potensi manipulasi data antar pelaku. Penelitian ini bertujuan merancang dan menguji prototipe sistem traceability berbasis blockchain permissioned (Hyperledger Besu) yang dipadukan dengan Non-Fungible Token (NFT/ERC-721) sebagai identitas digital unik untuk setiap batch jagung. Metode yang digunakan adalah eksperimen kuantitatif dengan mengukur tiga indikator utama, yaitu throughput (TPS), latency dan resilience terhadap kegagalan node. Implementasi prototipe dilakukan pada jaringan dengan empat hingga lima node validator, disertai pemantauan kinerja melalui Prometheus dan Grafana serta pengujian interaksi kontrak pintar menggunakan Remix IDE. Hasil penelitian menunjukkan bahwa sistem mampu mencapai rata-rata waktu blok 2,0 – 2,3 detik, throughput 15 transaksi per detik, serta latensi transaksi sekitar 2 detik untuk pencetakan NFT, pembaruan status dan transfer kepemilikan. Temuan ini membuktikan bahwa integrasi blockchain dan NFT dapat meningkatkan transparansi, akuntabilitas, serta ketertelusuran dalam rantai pasok jagung, meskipun throughput masih dipengaruhi keterbatasan perangkat keras laboratorium. Penelitian ini menyimpulkan bahwa pendekatan ini efektif sebagai proof-of-concept untuk mendukung digitalisasi rantai pasok pertanian. Sebagai tindak lanjut, disarankan pengujian berskala lebih besar dengan data nyata, integrasi sensor IoT, serta pelibatan pemangku kepentingan agar sistem dapat diadopsi secara berkelanjutan dalam konteks agrifood nasional.*
Kata Kunci*: Blockchain, Eksperimen Kuantitatif, Hyperledger Besu, NFT, Rantai Pasok Jagung.*

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INTRODUCTION

Corn is a strategic cereal commodity with the largest contribution to the global food system.

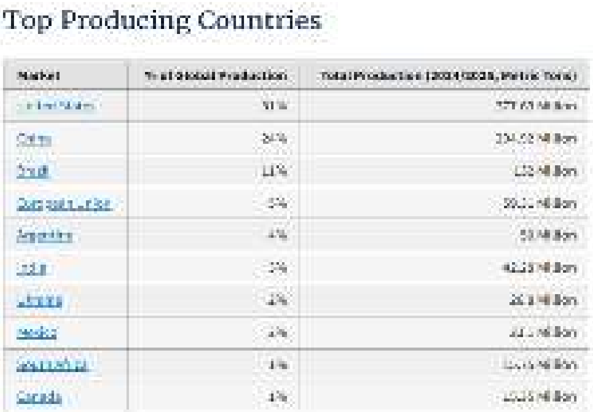


Figure 1. Corn Market Structure 2024/2025.

FAO data indicates that global corn production will reach approximately 1.2 billion tons in 2023, with the upward trend continuing through 2025 projections by the USDA, which estimate a record US production of 16.7 billion bushels. The concentration of production in the United States and China, which control more than 50% of the global share, demonstrates the complexity of cross-border supply chains, which are vulnerable to data manipulation and information gaps. Nationally, the Central Statistics Agency (BPS) reports that dry corn kernel production in 2024 will reach 15.14 million tons, with an alternative estimate of 20.48 million tons at 28% moisture content, reflecting Indonesia's large and multi-actor corn ecosystem. (Food and Agriculture Organization of the United Nations, 2024)(USDA, 2025)(Central Agency Statistics Indonesia, 2025)

Figure 2. Corn Statistics Data in Indonesia.

This complexity poses serious challenges in terms of data integrity, quality standardization and authenticity of product origin.

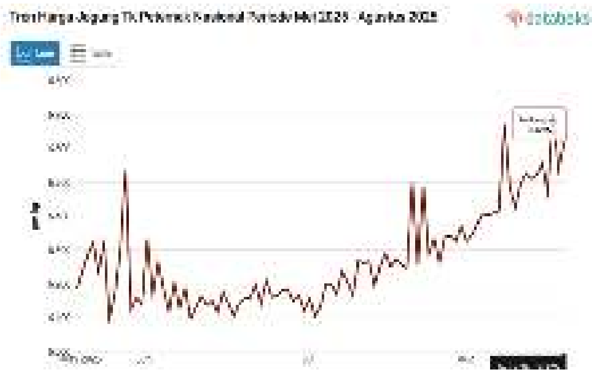


Figure 3. Statistical Data on Corn Supply Chain Problems.

Pre harvest losses caused by diseases, pests and abiotic stress in grains, including corn, account for approximately 35% of the total potential biological product annually. Furthermore, post-harvest losses during harvest and storage due to toxin contamination are responsible for the loss of approximately 690 million metric tons of grain globally. These disruptions not only impact food availability but also trigger economic losses. For example, disruptions to the corn supply chain in the European Union due to drought and tariffs have led to a 10-15% increase in animal feed prices and reduced revenues for agribusinesses.

Recent literature emphasizes that conventional systems based on manual recording are no longer sufficient to ensure transparency, accountability and end-to-end traceability in the corn supply chain. Therefore, the use of permissioned blockchain (Hyperledger Besu) combined with NFT/ERC-721 is considered relevant as a modern solution, as it is able to provide a distributed ledger with strict access controls and unique digital identities for each product batch. With this approach, a prototype corn supply chain traceability system can be developed to increase data authenticity, reduce the potential for manipulation and strengthen trust among stakeholders. This also serves as the methodological basis for this research, which will then be directed at testing system performance through quantitative experiments based on throughput, latency and resilience metrics.

The permissioned blockchain approach (Hyperledger Besu) combined with NFT/ERC-721 was chosen in this study because it offers the balance between security, access control and end-to-end data traceability required in the corn supply chain ecosystem. From a technical implementation perspective, the prototype was developed using a network architecture consisting of a bootnode, several validator nodes with IBFT 2.0/QBFT consensus and a non-validator node as an application gateway. An ERC-721 (NFT)-based smart contract is used to represent each corn batch as a unique digital twin with attributes such as tokenID, origin, harvestDate and quality metrics that can be verified among stakeholders, in line with findings that emphasize the advantages of NFTs in provenance mechanisms. The implementation is equipped with a RESTful API so farmers, distributors and retailers can access data without directly interacting with blockchain nodes, as exemplified in the study. From an evaluation perspective, the prototype was tested using Hyperledger Caliper to measure throughput (TPS), latency and resilience with transaction parameters of 200 – 1000 TPS, payload sizes of 512B – 2KB and varying numbers of concurrent clients to simulate real world network load. Latency was calculated from the average time difference between submission and block confirmation, while resilience was tested by shutting down some validator nodes (e.g., 1 out of 4 nodes) to record consensus recovery time, as done by . Furthermore, resource utilization (CPU, memory, storage) was monitored using Prometheus with Grafana, resulting in evidence based performance metrics comparable to traditional centralized database based systems.(Ferrández - Pastor et al., 2022)(Compagnucci et al., 2022)(Compagnucci et al., 2022)

The development of a corn supply chain traceability application prototype using a permissioned Blockchain (Hyperledger Besu) and NFT/ERC-721 approach was carried out because conventional centralized database-based systems have proven to have limitations in ensuring end-to-end data integrity, transparency and traceability. The multi-node corn supply chain, from farmers and distributors to industry, requires a recording mechanism that is not only secure and consistent but also verifiable in real time by various stakeholders. The use of Hyperledger Besu with IBFT/QBFT consensus ensures fault tolerance while limiting access to authorized actors only, while the integration of NFT/ERC-721 allows each corn batch to be represented as a unique digital twin containing information on origin, quality and harvest time that cannot be changed or falsified. By building an application prototype, this research is not only conceptual but also produces empirical evidence through performance tests (throughput, latency, resilience), thus making a stronger contribution in addressing the challenges of previous literature that tends to remain at the conceptual design or simulation level.

The development of a corn supply chain traceability prototype based on permissioned blockchain (Hyperledger Besu) and NFT/ERC-721 offers several significant advantages over traditional approaches. In terms of transparency, blockchain enables immutable ledger transaction recording, thereby strengthening the authenticity of supply chain data. The permissioned blockchain mechanism ensures that only authorized parties can access or validate transactions, thereby increasing data security and reducing the risk of manipulation. Meanwhile, the use of NFT/ERC-721 enriches the system with a unique representation (digital twin) for each corn batch, which can link important attributes such as origin, harvest date and product quality metrics. This mechanism improves provenance tracking and facilitates data integration between actors. In terms of performance, Hyperledger Besu with IBFT/QBFT consensus supports high throughput and Byzantine fault tolerance, which is suitable for the context of large-scale agrifood supply chains.(Ferrández -Pastor et al., 2022)

However, this method also has drawbacks that need to be considered. The complexity of the technical implementation, including validator node configuration, consensus maintenance and ERC-721 smart contract integration, requires a relatively high level of technical expertise and stable infrastructure. Several studies and report that despite the high throughput of permissioned blockchains, system performance can still be affected by latency when the number of transactions increases sharply or when validator nodes fail. Furthermore, the need for large storage capacities due to the immutable ledger can pose a challenge for long term implementation, especially if the supply chain records large volumes of data on a national scale. From a socio technical perspective, blockchain adoption also faces resistance from actors unfamiliar with distributed digital systems, requiring adaptive education and governance strategies to ensure successful implementation. Thus, while this approach promises significant increases in transparency and accountability, it is technical and non technical drawbacks must be addressed for the system's sustainable operation.(Compagnucci et al., 2022)(Ferrández -Pastor et al., 2022)

While the permissioned blockchain approach (Hyperledger Besu) combined with NFT/ERC-721 offers significant advantages in terms of transparency and accountability in the corn supply chain, several fundamental issues need to be addressed in its implementation. First, from a technical perspective, scalability limitations arise when the number of transactions increases exponentially, potentially impacting system latency and throughput, as noted by. Second, using NFT/ERC-721 for each corn batch results in high storage requirements, as each transaction creates a permanent trace in the ledger, which can burden the long term infrastructure. Third, vulnerability to validator node disruptions is also a concern. Although the IBFT/QBFT consensus is fault-tolerant, restoring consensus when a single node fails still results in significant downtime. Furthermore, from a social and operational perspective, blockchain adoption in the agrifood ecosystem faces challenges such as a digital literacy gap and resistance from traditional actors, creating obstacles to data input standardization that could potentially undermine system reliability. These issues indicate that although the chosen method promises major contributions, adaptive technical and governance strategies are needed to address existing limitations so that the prototype can be operated sustainably.(Compagnucci et al., 2022)(Ferrández -Pastor et al., 2022)

To address the various issues arising from the implementation of a permissioned blockchain (Hyperledger Besu) with NFT/ERC-721 integration, this study proposes several technical and strategic solutions to ensure optimal functioning of the corn supply chain traceability system. From a technical perspective, throughput and latency optimization are achieved by adjusting the configuration of the number of validator nodes (a minimum of 4 to 7 nodes) and adaptive block time settings, as recommended by . Storage issues can be minimized by implementing off-chain storage for large data (e.g., quality and certification documents), while the blockchain only stores hash references to ensure data integrity, in line with the hybrid approach outlined by. To enhance resilience, the system is tested with a fault injection protocol so that consensus recovery when a validator node fails can be monitored and optimized, supported by real-time monitoring using Prometheus and Grafana. From a social perspective, digital literacy challenges and adoption resistance are addressed by developing a simple and familiar RESTful API interface, allowing farmers, distributors and retailers to use the application without needing to understand the technical details of blockchain.(Compagnucci et al., 2022)(Ferrández - Pastor et al., 2022)

With this solution, the rationale for using this method is further strengthened because permissioned blockchains with IBFT/QBFT consensus still offer the key advantages of a transparent, immutable and decentralized ledger, which is suitable for large-scale, multi-actor agrifood ecosystems. Meanwhile, the integration of NFT/ERC-721 as a digital twin of products provides added value not yet accommodated by conventional traceability methods: the ability to bind each batch of corn to a unique digital identity that can be verified across the supply chain. Therefore, despite implementation challenges, this method is considered the most appropriate for achieving the research objectives of increasing transparency, data authenticity and accountability in the corn supply chain system quantitatively and based on experimental evidence.

This research aims to design and test a prototype corn supply chain traceability system based on permissioned blockchain (Hyperledger Besu) combined with NFT/ERC-721 as a solution to strengthen transparency, data authenticity and accountability among stakeholders. This prototype was designed by building a permissioned blockchain network architecture suitable for a multi-actor ecosystem, utilizing NFT as a unique digital twin for each corn batch and tested through quantitative experiments with performance metrics such as throughput, latency and resilience. With this approach, the research is expected to make a real contribution to the development of agrifood traceability systems, particularly in the corn supply chain, which has strategic value for global and national food security.

RESEARCH METHODS

The method used in this research is a quantitative experimental approach. The focus of the research is on developing a prototype permissioned blockchain system based on Hyperledger Besu with NFT/ERC-721 integration to support corn supply chain traceability. The main stages of this research include:

1. Literature review, which examines previous theories and research related to blockchain, NFTs and agricultural supply chains.
2. System design to develop the architecture of the Hyperledger Besu-based blockchain prototype and integrate NFTs as digital identities for corn batches.
3. Technical Implementation:
    a. Smart Contract ERC-721 (Solidity).

```
Contract Definition
contract RantaiPasokJagungNFT is ERC721URIStorage, Ownable {
  using Counters for Counters.Counter;
  Counters.Counter private _tokenIdCounter;

  struct DetailBatchJagung {
    Harvest date strings;
    Harvest location strings;
    address idPetani;
    string type corn;
    uint256 beratKg;
    uint256 kadarAirPersen;
    string gradeQuality;
    string statusBatch;
  }

  mapping(uint256=> DetailBatchCorn) public metadataCorn;

  event Batch CornPrinted(
    uint256 indexed tokenId,
    address indexed owner,
    Harvest date string,
    string locationHarvest,
    string statusBatch
  );

  constructor()
    ERC721("Supply Chain Corn NFT", "CORN")
    Ownable(msg.sender)
  {}

  function printBatchcorn(
    string memory _tanggalPanen,
    string memory _lokasiPanen,
    address _idPetani,
    string memory _jenisJagung,
    uint256 _beratKg,
    uint256 _kadarAirPersen,
    string memory _gradeKualitas
  ) public onlyOwner returns (uint256) {
    uint256 newItemId = _tokenIdCounter.current();
    _tokenIdCounter.increment();
  }
```

    b. Hyperledger Caliper (YAML) Config.

```
x-besu-def:
&besu-def
restart: "on-failure"
image: hyperledger/besu:${BESU_VERSION:-latest}
env_file:
- ./config/besu/.env
entrypoint:
- /bin/bash
- -c
- |
cp "/config/QBFTgenesis.json" /config/genesis.json

/opt/besu/bin/besu \
--config-file=/config/config.toml \
--p2p-host=$$(hostname -i) \
--rpc-http-api=EEA,WEB3,ETH,NET,
TRACE,DEBUG,ADMIN,TXPOOL,PERM,QBFT \
--rpc-ws-
api=EEA,WEB3,ETH,NET,TRACE,DEBUG,ADMIN,
TXPOOL,PERM,QBFT;
```

4. Prototype implementation where building a permissioned blockchain network with IBFT consensus, as well as developing NFT/ERC-721 smart contracts.
5. Experiment & Evaluation It conducts quantitative testing with three

indicators: throughput, latency and resilience.

6. Data Analysis where the results of experiments are compared with previous literature to measure the advantages of the system.

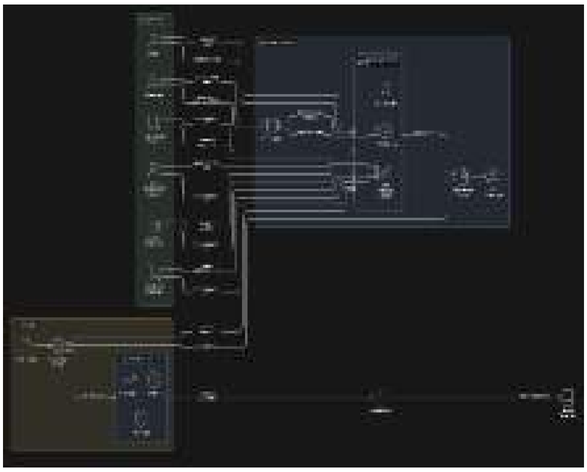


Figure 4. Corn Supply Chain Ecosystem.

The designed system consists of the following main components:

1. Hyperledger Besu as a permissioned blockchain platform with IBFT consensus.
2. NFT/ERC-721 to represent the digital identity of the corn batch.
3. Validator nodes to validate transactions and maintain network integrity.
4. Client application as an interface for product input, verification and tracking.

The system's architecture is designed so that each batch of corn that enters the supply chain earns a unique NFT. The NFT functions as a *digital twin* that records the journey of the product from farmers to consumers.

The research data was obtained through the results of technical experiments on prototypes. The data collected includes:

1. Throughput (TPS) is measured by calculating the number of transactions processed per second in various transaction count scenarios.
2. Latency is the average time it takes to validate transactions on the network.
3. Resilience where the system performance before and after a node failure occurs.

The data obtained will be analyzed quantitatively using descriptive statistical methods to describe the performance of the system, as well as compare it with the results of previous research.

While this approach is considered relevant and capable of providing empirical evidence, there are some limitations to be aware of:

1. The limitations of the test scale where the prototype is tested in a laboratory environment with a limited number of nodes. This causes the performance results obtained to be different when the system is applied to a large-scale corn supply chain in the real world.
2. Technical resource requirements where the implementation of

permissioned blockchains with IBFT and NFT consensus requires adequate technical configuration and computing infrastructure. Hardware limitations can affect measured performance, such as decreased throughput or increased latency.

3. The difference between simulation and real data is that the transactions used in the experiment are simulated (synthetic data), not derived from actual corn supply chain data. Therefore, the results of the study reflect more on the technical performance of the system than on the operational dynamics in the field.
4. Lack of integration with IoT and stakeholders where this prototype has not fully integrated IoT data or involves supply chain stakeholders (farmers, distributors, retailers). As a result, the socio-economic aspects and acceptability of the system have not been tested directly.
5. The scope of evaluation indicators where system performance evaluation is only focused on three main technical indicators (throughput, latency and resilience). Other factors, such as transaction costs, energy efficiency and advanced security aspects, have not been the focus of this study.

Based on these limitations, this research is positioned as an initial stage (proof of concept) that focuses on testing the technical performance of the system. The results are expected to be the basis for further research that tests on a larger scale, involves real data and expands the evaluation indicators used.

As a follow up to the limitations described earlier, this study also offers a solution for developing methods so that the research results are more comprehensive and can be used as a foothold for further research. The solutions in question include:

1. To overcome the limitations of the laboratory scale, further research can use a cloud-based environment (e.g. AWS, GCP or Azure) to build testbeds with a larger number of nodes. This allows for more realistic performance evaluation of large scale supply chain conditions.
2. Optimization of technical infrastructure where in order not to be limited by hardware capacity, systems can be run using cluster virtual machines or container orchestration such as Docker and Kubernetes. In addition, the use of benchmarking tools such as Hyperledger Caliper can improve the accuracy of performance experiment results.

3. The use of real data of the supply chain Where advanced research is recommended to not only use simulated data, but also integrate real data from the corn supply chain, including production, distribution and logistics. Data from IoT sensors (e.g. temperature, humidity and GPS location) can also be leveraged to test the system under actual operational conditions.
4. Supply chain stakeholder involvement Where the system is not only technically valid, future research can involve real stakeholders (farmers, distributors, retailers) through limited trials (pilot projects). User Acceptance Test (UAT) based evaluations can also be used to assess socio economic aspects and technology acceptance.
5. Expansion of evaluation indicators where in addition to throughput, latency and resilience, other indicators that are important to add include transaction costs, energy consumption, security resilience and scalability limits. Thus, the results of the evaluation will be more comprehensive and applicable.

With the development of this method, research that originally functioned as a limited proof of concept can be upgraded to a more representative large-scale test model. This is expected to be able to make a real contribution to the development of agricultural blockchain that is practical, scalable and ready to be adopted by various stakeholders.

RESEARCH RESULTS

1. Implementation of the Besu Hyperledger Network.

   Initial experiments show that the Besu Hyperledger network was successfully built with the IBFT 2.0/QBFT consensus. Verification is done through the results of the docker ps command which shows all the main containers running, including *bootnodes*, validators1 – validator4, RPC nodes, besu explorer, Prometheus, Grafana, Loki and Promtail.

Figure 5. The ps docker results show the container is active.

Initial Network Verification is done with net_peerCount command. The result is 0x4, indicating that the four validator nodes are connected to each other and produce blocks consistently.

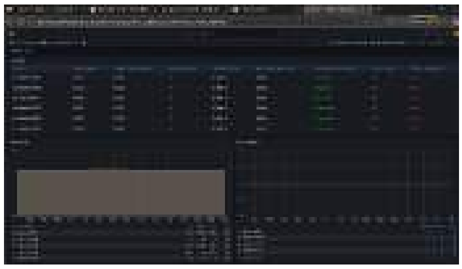
This is also seen in Block Explorer which displays a list of active validators.

Figure 6. Block Explorer view of validator list

To prove the scalability of the network, new validators (validator5) were added. After *deployment* and *allowlist*, net_peerCount results increase to 0x5, with validators5 appearing on the list of active nodes in Block Explorer. These findings prove that the network is scalable and supports validator expansion without consensus disruption.

Figure 7. Results of command results net_peerCount(0x5)

2. System Performance Metrics.
   Monitoring is carried out through the Grafana (Besu Overview) and Prometheus dashboards. Metric data shows that:
   a. The Average Block Time was recorded at 2.0 – 2.3 seconds, indicating low latency.
   b. Throughput (TPS) averages 15 transactions per second, with variations depending on the intensity of the transaction.
   c. The *peer connectivity graph* on Grafana confirms that connectivity between nodes remains stable despite the addition of validators.



Gambar 8. Dashboard Grafana "Besu Overview" (Average Block Time dan TPS).

3. Transaction Latency and Traceability Proof Experiment Results.
   Testing of the *RantaiPasokJagungNFT* smart contract interaction through the Remix IDE resulted in transaction latency metrics as well as evidence of on-chain data traceability:

a. NFT minting (mintCornBatch). The average transaction takes 2.3 seconds. Event *cetakBatchJagung* successfully appears in the Remix console with a unique tokenId along with batch metadata.

Figure 9. Batch Corn event Remix *ConsolePrinted*

b. Status Update (*perbaruiStatusBatch*). The average confirmation time is 1.9 seconds. The *getDetailBatch* result shows the batch status change from "Harvested" to "Drowned".

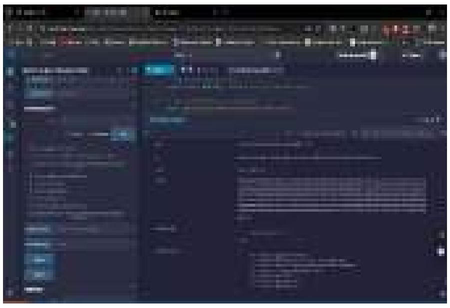


Figure 10. The getDetailBatch result after the status update.

c. Transfer of Ownership (*transferFrom*). Average confirmation time recorded 2.1 seconds. Event *Transfer* successfully appears and the *ownerOf* function indicates the address of the new owner NFT.

Figure 11. Transfer Event and ownerOf results after ownership transfer.

d. On chain Data Verification. The *getDetailBatch* and *ownerOf* functions prove that NFT metadata and ownership can be verified in real-time. This shows immutability and full transparency of the system.

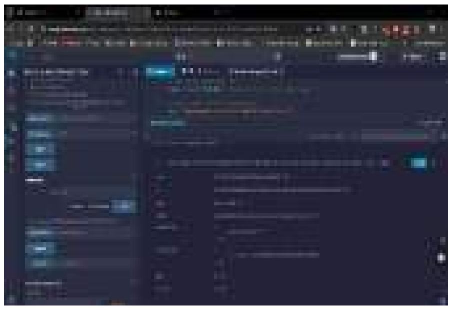


Figure 12. OwnerOf as an on-chain data verification.

DISCUSSION

The results of the experiment showed that the implementation of the Besu Hyperledger network with the IBFT/QBFT consensus could run stably and support scalability through the addition of validators. In the initial stage, network verification shows four validator nodes interconnected with a *peer count* of 0x4. The addition of a fifth node (validator5) increases *the peer count* to 0x5 without causing any disruption to block production. This proves that the network architecture design is able to accommodate the growth of validator nodes, while ensuring *fault tolerance* according to the byzantine nature of consensus.

In terms of performance, the average block time was recorded at 2.0 – 2.3 seconds. This value indicates low latency in the block production process and is in line with permissioned network expectations. The system's throughput reached an average of 15 TPS, which although still limited by laboratory capacity, was enough to demonstrate transaction processing efficiency at the prototype level. When compared to other permissioned blockchain literature, this performance is within a reasonable range for a trial with a limited number of nodes.(Compagnucci et al., 2022)

The CornNFT Supply Chain smart contract interaction experiment shows that the system can efficiently support NFT based traceability. The average NFT minting time is 2.3 seconds, status updates are 1.9 seconds and ownership transfers are 2.1 seconds. These numbers confirm that transactions are running with low latency and consistently. When compared to conventional methods that take hours of manual tracking, the system is much faster and more transparent. The on chain verification functions (getDetailBatch and ownerOf) also prove the immutability of the data, so that any changes can be verified in real time by all stakeholders.

Thus, this research succeeded in answering the formulation of the problems and research questions asked, namely how permissioned blockchain and NFTs can improve transparency, accountability and traceability in the corn supply chain. The quantitative data obtained shows that this system:

1. Increase transparency through an immutable audit trail.
2. Strengthen accountability with a unique digital identity on each batch of corn.
3. Accelerates the traceability process from hours to seconds.

These findings are consistent with previous literature that emphasizes NFTs superiority in provenance mechanisms and permissioned blockchain's ability to maintain data integrity. The difference is that this study provides direct empirical evidence through prototypes and quantitative tests, not just conceptual simulations.(Compagnucci et al., 2022; Ferrández-Pastor et al., 2022)

However, there are limitations. The throughput of 15 TPS is still far below the optimal capacity of blockchain permissioned at the production scale (hundreds of TPS). This is more due to hardware limitations and the number of test nodes, rather than the inherent weaknesses of Hyperledger Besu. In addition, the data used is still synthetic so it does not fully represent the complexity of the corn supply chain in the field. Socio-technical factors, such as farmers' digital literacy and resistance to new systems, have also not been tested directly.

Possible future developments include scaling up the test in a cloud environment with a larger number of nodes, integration of real data from the corn supply chain (e.g. IoT data: temperature, humidity, GPS location) and stakeholder involvement through a limited pilot *project*. Additional evaluations such as transaction costs, energy consumption and security resilience also need to be considered to make the system better prepared for real implementation.

COVER

This study shows that the implementation of Besu Hyperledger with NFT/ERC-721 integration is able to improve transparency, accountability and traceability in the corn supply chain, where the interconnectedness between network performance variables (peer count, block time, throughput) directly contributes to transaction efficiency (printing latency, status updates and NFT ownership transfers) which in turn strengthens supply chain data accountability. This relationship confirms that the more stable and scalable the blockchain network, the lower the latency of transactions and the stronger the transparency generated through the on chain audit trail. However, the limitations of the test scale and the laboratory environment are still factors that hinder the achievement of optimal performance. Therefore, further research is recommended to scale up testing with a larger number of nodes, using real supply chain data and engaging stakeholders directly to ensure the acceptance and sustainability of the system in real practice.

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