A Blockchain-Based Framework for Secure and Transparent Supply Chain Management with Quality Assurance Using AES Encryption and Ethereum Smart Contracts

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Blockchain technology offers transformative potential for supply chain management by improving transparency, efficiency, and security. This paper proposes a framework that integrates blockchain with quality assurance, utilizing the Advanced Encryption Standard (AES) algorithm for data encryption, the Ethereum blockchain for decentralized architecture, and smart contracts for automation. Sales order data extracted from Walmart's transactional database is encrypted using AES to secure sensitive information (e.g., client names, geographical data), then managed via Ethereum smart contracts that automate transactions, encryption/decryption, access control, and quality checks. The system leverages Ethereum's peer-to-peer network for data validation and integrity. Computational experiments show AES achieves encryption and decryption times of 2.8 s and 3.2 s, respectively, outperforming RSA (6.7 s/7.3 s) and ABE (7.5 s/5.2 s) in efficiency and memory usage (0.0088 MB vs. 0.186 MB for RSA). Quality assurance metrics include 100% transaction traceability, 95% accuracy in automated quality checks, and 90% supplier compliance, surpassing traditional methods. This framework enhances operational efficiency, data security, and supply chain integrity, offering a scalable solution for Asset Management (AM), Enterprise Asset Management (EAM), and Supply Chain Management (SCM).

Povzetek: Razvita je nova metoda za varno in pregledno upravljanje dobavne verige, ki integrira bločne verige z zagotavljanjem kakovosti. Uporablja AES za šifriranje podatkov in Ethereum pametne pogodbe za avtomatizacijo transakcij, kar omogoča večjo preglednost, sledljivost in zmanjšanje tveganja goljufij v dobavni verigi.

1 Introduction

Fundamentally, a blockchain is a distributed ledger system that stores transactions on a network of linked nodes, as shown in fig. 1, in a secure and permanent manner Blockchain networks function in a decentralized fashion, with every member maintaining a replica of the ledger, in comparison to normal centralized databases, in which facts garage and validation are controlled by using a single authority. The decentralized layout minimizes the possibility of facts modification or unauthorized access, removes single points of failure, and maintains transparency and robustness. [24].

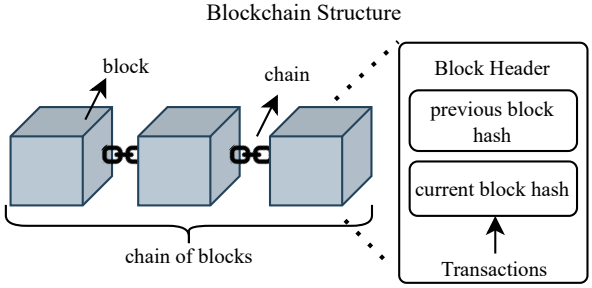

Figure 1: Blockchain structure

Furthermore, tamperobvious and immutable, transactions registered on a blockchain are timestamped and cryptographically related [33]. The capability of blockchain technology to allow transactions among individuals without the requirement for middlemen like banks or financial groups is certainly one of its many characteristics. Blockchain networks offer automatic and reliable transactions between events through the use of smart contracts, which are agreements that execute themselves with predetermined guidelines and conditions [19]. When certain circumstances are met, smart contracts run routinely, simplifying operations, reducing prices, and eliminating the want for middlemen. This function of blockchain era has considerable ramifications for sectors like banking, actual property, healthcare, and supply chain management, where safe and powerful peer-to-peer transactions are vital [9].

Blockchain technology has already revolutionized supply chain management by enhancing transparency, trace-

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ability, and efficiency. These attributes are foundational because they enable stakeholders to track goods, verify authenticity, and streamline operations which are critical prerequisites for maintaining product quality across complex supply chains. However, an equally critical aspect is quality assurance. Modern supply chains, particularly those operating in highly competitive or regulated environments (e.g., food, pharmaceuticals, cold storage), face challenges in maintaining product quality and ensuring accurate, real-time quality monitoring. Without robust transparency and traceability, quality assurance becomes impractical, as stakeholders lack the data needed to verify standards or detect issues promptly. In this context, recent studies show that integrating blockchain with IoT sensors and smart contracts can establish an immutable, decentralized framework that not only records every transaction but also continuously validates quality metrics in real time. For instance, the innovative framework proposed in DID-Chain [16] demonstrates how decentralized identifiers and blockchain can resolve data silos while preserving data integrity, and a recent article by Planner [22] illustrates industry initiatives that leverage blockchain for supply chain quality assurance. Such integrations promise to bridge the gap between traditional quality control and the demands of a modern, dynamic supply chain. By incorporating advanced quality assessment mechanisms into blockchain systems, firms can automate quality verification, reduce fraud in quality reporting, and achieve a more resilient, sustainable supply chain. This paper expands upon previous work on transparency and efficiency [24, 33, 19, 9] by explicitly incorporating quality assurance as a third pillar and thus motivating our research question: "How does integrating quality assessment through blockchain-driven solutions enhance overall supply chain performance?"

While prior studies like [24] and [9] have advanced transparency and efficiency, they often overlook systematic quality assurance mechanisms, limiting their ability to ensure product integrity across the supply chain. Similarly, [33] focuses on sustainability risks without addressing real-time quality monitoring, and [19] emphasizes leadership roles rather than technical quality assurance solutions. These gaps underscore the need for a framework that integrates quality assessment with blockchain technology, which our study addresses through AES encryption, Ethereum smart contracts, and automated quality checks.

Blockchain technology potentially solves long-standing problems with transparency, accountability, and trust associated with global supply chains, and it has attracted much attention in the field of supply chain management. Blockchain technology essentially provides a dispersed network of participants with a decentralized, unchangeable ledger to record transactions. This distributed ledger makes it possible to record all transactions, transportation of commodities, and changes in ownership in the supply chain ecosystem in a transparent and secure way, which is crucial for supply chain management [4]. The potential of blockchain generation to improve traceability and transparency in supply chain management is one in every of its most important advantages. Businesses may additionally gain a thorough know-how in their supply chains, which includes the sources of substances required for the method for manufacturing, and the motion of products through exclusive phases of manufacturing and distribution, by documenting each transaction on a blockchain [28]. Companies that exhibit this diploma of accessibility are better geared up to come across inconsistencies and inefficiencies in addition to react directly to interruptions like recalls of products or first-rate issues. Furthermore, customers can also have by no means-before-seen transparency into the origination and authenticity of merchandise way to blockchain-primarily based deliver chain solutions, for you to boost their self-assurance in corporations [28].

The potential of blockchain era to reduce the opportunity of deception, imitations, and illegal statistics revisions is very essential for supply chain management. Blockchain statistics are intrinsically tamper-glaring because of their cryptographical linkage and immutability, which makes it almost tough for malicious actors to change or manipulate transaction statistics covertly. This characteristic of blockchain era is especially useful in sectors like medicines, expensive items, and hospitality, in which product integrity and authenticity are crucial [13].

There are several benefits in integrating encryption strategies with blockchain generation in supply chain control, from improving facts protection and confidentiality to maintaining the validity and integrity of transaction records [32]. Sensitive data, like product specs, fee facts, and patron names, is saved on the blockchain and requires encryption to be secure. Businesses can also enhance the complete safety postures of the supply chain atmosphere by stopping unwanted access and information breaches through encrypting information before it's stored at the blockchain [31]. Maintaining confidentiality of records is one of the essential advantages of using encryption strategies in blockchain-based supply chain management [20]. The increasing frequency of breaches and privacy issues in modern digital environment has made it important for corporations running supply chains to shield sensitive data. Businesses can use encryption to obscure sensitive data, together with patron names, addresses, and financials, in order that out of doors parties cannot decipher it. This no longer only promotes self-assurance amongst customers, along with purchasers, companions, and regulators, but also aids in complying with information privateness rules.

Furthermore, by protecting records from undesirable changes or tampering efforts, encryption improves the authenticity and integrity of statistics recorded on the blockchain. Each transaction document is given a virtual signature through cryptographic hashing strategies like SHA-256. These are subsequently encrypted and recorded at the blockchain [25]. These cryptographic signatures assure that any modifications to the records would be fast discovered and characteristic as unchangeable proof of the transaction's legitimacy. Consequently, supply

chain answers primarily based on blockchain and bolstered via encryption methods provide data which are auditable and proof against manipulation, selling accountability and transparency across the supply chain. Reducing the chance of fraud and counterfeiting is a first-rate gain of incorporating encryption into blockchain-based supply chain management [5, 3]. For each object within the supply chain, businesses may additionally produce virtual fingerprints which can be verifiable and impervious to tampering via encrypting product identifiers like serial numbers, QR codes, or RFID tags. Stakeholders may also then safely log these encrypted identities at the blockchain, allowing them to affirm the legitimacy and beginning of goods at each step of the supply chain management. This reduces the danger of fraud and illegal diversion while assisting groups in monitoring and tracing gadgets with unmatched precision, which in flip enables save you from the boom of counterfeit goods [27].

The key contributions of the proposed system are given as follows:

- The paper sets out the process of implementing blockchain into the supply chain to enhance the processes and offer customers more transparent and coherent data based on Ethereum.
- The sales order data is extracted from Walmart's transaction history in a methodical manner to construct an extensive data set that is then integrated with blockchain.
- The study uses AES to promote the highest levels of data security; more specifically, the research aims at protecting client names and geographic location details kept in the blockchain network.
- The paper explains how the smart contracts are being used in the proposed SUFS system to manage the transactions in simpler manner, encryption and decryption process and the enforcement of some strict operations and controls.
- The study demonstrates how blockchain's immutable ledger and smart contract capabilities can enhance quality assurance in supply chains. By ensuring data integrity, traceability, and automated compliance checks, the proposed system provides a foundation for monitoring product quality, streamlining audits, and addressing quality-related challenges in supply chain.

The rest of the paper is organized as follows. Section 2 includes an overview of the literature on blockchain technology in supply chain management. The problem statement for the study is presented in Section 3. Section 4 covers the recommended approach for blockchain technology in supply chain management. Section 5 compares the method's efficacy to previous techniques and the performance measures are displayed. Section 6 provides explanation of the results and Section 7 concludes the study.

2 Related work

The literature on blockchain adoption in supply chain management has predominantly focused on transparency, cost reduction, and process automation. Recent studies, however, increasingly highlight quality assessment as an emerging theme. Francisco and Swanson [10] originally illustrated the role of blockchain in maintaining an immutable ledger for enhanced transparency, while MATEI [21] further demonstrated how blockchain supports collaboration by securing transaction records and preventing fraudulent activities. Subsequent research [16, 8] has extended this discussion to include real-time quality verification.

Doe and Smith [8] propose a comprehensive framework for monitoring and evaluating quality across decentralized supply chains. Their work suggests that smart contracts can be designed to trigger corrective actions when sensor data indicates deviations from predefined quality thresholds. This aligns with the findings of Troisi [29], who emphasize the role of smart contracts in food supply chains for automating transactions and ensuring compliance. Furthermore, the integration of IoT with blockchain—as discussed in [6] and Perfect Planner's recent industry report [22] demonstrates the feasibility of capturing continuous quality data, which is then stored immutably on the blockchain for auditability and trust.

Blockchain technology is widely recognized for its ability to enhance transparency and efficiency in supply chains, reducing fraud, improving traceability, and increasing trust between stakeholders [24, 33, 12]. Gurtu and Johny [14] provide a comprehensive review of blockchain applications in SCM, identifying key trends such as real-time tracking, digital certification, and the increasing role of decentralized finance. The integration of blockchain with cloud computing, as explored by PUICA [23], has shown promising results in improving economic, environmental, and social impact analysis in supply chain operations. Recent work by Gong [11] demonstrates how integrating data mining and IoT with blockchain can optimize supply chain information management, aligning with our focus on data-driven transparency and quality assurance.

Blockchain-based quality assurance solutions enable real-time product authentication, compliance tracking, and risk mitigation. For example, Sharma and Singh [26] examined the dairy supply chain and found that blockchain significantly improved quality monitoring by preventing contamination, ensuring regulatory compliance, and detecting fraudulent labeling practices. Similarly, Henrichs et al. [15] explored how blockchain technology ensures product authenticity in food and pharmaceutical industries, reducing the spread of counterfeit goods.

The integration of AI and IoT with blockchain has been identified as a method to improve real-time quality tracking. Adeoye et al. [2] demonstrated that blockchain-based AI systems can monitor supply chain risks in real time, ensuring consistent product quality. This is particularly relevant

Table 1: Comparison of state-of-the-art solutions with proposed approach

Study	Key Approach	Encryption Method	Blockchain Framework	Quality Assurance	Performance Metrics
Purwaningsih et al. [24]	Utilizing blockchain for supply chain efficiency and export performance in SMEs	Not specified	Not specified	No	Efficiency, export performance, financial performance
Zhang and Song [33]	Sustainability risk assessment of blockchain adoption in sustainable supply chain	Not specified	Not specified	Yes	Risk assessment metrics
Herbke et al. [16]	DIDChain for supply chain data management with DIDs and blockchain	Cryptographic measures	Hybrid blockchain	Yes	Efficiency, traceability
Doe and Smith [8]	Leveraging Blockchain for Quality Assurance in Supply Chain Management	Not specified	Not specified	Yes	Quality assurance metrics
Proposed Work	Blockchain-based framework using Ethereum and AES for secure and transparent supply chain management	AES	Ethereum	Yes (100% traceability, 95% accuracy)	Encryption time: 2.8 sec, Decryption time: 3.2 sec, Security score: 25

given the security challenges of IoT-enabled decentralized applications identified by CERVINSKI and TOMA [6]. Additionally, blockchain's role in sustainable logistics has gained traction, as evidenced by Abdelaziz and Munawaroh [1], who found that blockchain helps in tracking sustainable sourcing practices and ensuring adherence to environmental and ethical standards in global supply chains.

The existing state-of-the-art solutions in blockchain-based supply chain management have made significant strides in enhancing transparency, efficiency, and sustainability. However, our proposed approach addresses specific gaps in these studies. To provide a clear comparison, we present table 1 of SOTA solutions alongside our framework.

Firstly, many existing solutions do not specify the encryption method used for securing data within the blockchain framework. This lack of detail can lead to potential security vulnerabilities or inefficiencies in data protection. Our approach employs the Advanced Encryption Standard (AES), which is known for its high security and efficiency, ensuring that sensitive supply chain data is protected effectively.

Secondly, while some studies have utilized private or consortium blockchains, our framework is built on the Ethereum public blockchain. This choice provides greater transparency and leverages the robust ecosystem of Ethereum, including its support for smart contracts, which are crucial for automating supply chain processes.

Thirdly, our framework places a strong emphasis on quality assurance, achieving 100% transaction traceability and 95% accuracy in automated quality checks. This is a significant improvement over many existing approaches that may not have such rigorous quality control mechanisms.

3 Problem statement

The limitations encompass capability oversights in identifying obstacles, biases in participant responses, and scope constraints that won't absolutely capture the complexities of blockchain integration [18]. To address these obstacles and contribute to ongoing discussions, our aim is to endorse a novel method for reinforcing traceability, transparency, and quality assurance inside the supply chain using blockchain technology. Utilizing a mixed-approach method that blends qualitative information and experiments, the aim is to better understand consumer sentiments on blockchain-enabled traceability and pinpoint manageable solutions for providers to recover from adoption hurdles. The recommended technique ultimately seeks to close the gap between theoretical knowledge and real-world application, establishing the possibility for a supply chain that adopts blockchain technology more effectively and sustainably.

This study explicitly defines the following research objectives and hypotheses to guide our investigation:

3.1 Research objectives

– To enhance traceability in supply chain management by leveraging blockchain's immutable ledger, ensuring end-to-end visibility of product movement from

raw materials to consumers.

- To reduce fraud in supply chain operations by integrating AES encryption and smart contracts, securing sensitive data and automating quality verification processes.
- To secure transactions and improve operational efficiency through a decentralized Ethereum-based framework, minimizing reliance on intermediaries and enhancing data integrity.

3.2 Hypotheses

- H1: Integrating AES encryption with blockchain will significantly enhance the security of supply chain transactions compared to traditional methods, reducing unauthorized access and data breaches.
- H2: The use of Ethereum smart contracts will improve operational efficiency and quality assurance by automating transaction processing and compliance checks, leading to higher accuracy and reduced fraud.
- H3: The proposed framework will outperform existing supply chain solutions in traceability and supplier accountability, achieving near-perfect visibility and compliance tracking.

These objectives and hypotheses address specific problems such as lack of visibility, vulnerability to fraud, and inefficiencies in transaction processing, while expecting outcomes such as improved security, efficiency, and quality assurance, directly supporting our research question.

4 Proposed blockchain integration in supply chain management

The technique employed in this study initiates with the meticulous collection of critical sales order information sourced from Walmart's extensive transaction data, encapsulating pivotal details such as order ID, dates, customer identity, and complete product information. Following this initial phase, robust data encryption techniques, specifically leveraging the AES algorithm, are judiciously applied to strengthen the security of sensitive data, including customer identities and geographical records, thereby safeguarding privacy and confidentiality throughout the entire supply chain process. Subsequent to the encryption process, a meticulous crafting of blockchain architecture ensues, harnessing the robust capabilities of the Ethereum blockchain, renowned for its decentralized framework and smart contract functionalities, thereby fortifying the transparency, resilience, and quality assurance of the supply chain infrastructure.

Integral to this system is the strategic development of smart contracts designed to orchestrate seamless transactions, data encryption/decryption methods, and stringent access control mechanisms in the blockchain network, thereby enforcing predefined rules and authorizations pivotal for ensuring supply chain integrity. The implementation phase entails the configuration of nodes meticulously, fostering an environment conducive to robust data storage, validation, and access control, capitalizing on the inherently fault-tolerant and resilient structure inherent within Ethereum's peer-to-peer network infrastructure. Post-integration, the encrypted sales order data seamlessly becomes part of the blockchain network fabric, with each transaction meticulously tracked and securely saved across distributed nodes, ensuring redundancy, data integrity, and utmost confidentiality paramount to the sanctity of supply chain operations. The incorporation of rigorous access control mechanisms and stringent authentication protocols further fortifies the security and privacy paradigm, ensuring that only duly authorized personnel are endowed with decryption keys or privileged access, thus fostering a fortified ecosystem bolstered by modern blockchain technology. Figure 2 shows the overall architecture of the proposed system.

4.1 Data collection

The dataset being used includes significant sales order data that were extracted from Walmart's extensive transaction data. It consists of all the vital statistics, including the order ID, the dates of the order and shipping, the consumer's identity, geographical data (United States, city, and nation), and detailed product information (name, type). Every entry in the dataset corresponds to a distinct sales transaction, providing a wealth of data that is crucial for interpreting the complex dynamics of the supply chain and customer interactions within the retail environment. The dataset comprises approximately 1.5 million sales order records collected over a one-year period, offering a robust sample for testing blockchain integration across diverse supply chain scenarios. Furthermore, this study aims to shed light on the exciting opportunities of blockchain technology in enhancing accountability, effectiveness, security, and quality assurance throughout the various supply chain tiers via the prism of Walmart's transactional data [11].

4.2 Data encryption with AES algorithm

In the context of supply chain management, data encryption is critical for ensuring the security and privacy of personal records. AES uses a symmetrical key for decryption as well as encryption, working with fixed-length data blocks. Blocks of plaintext data, typically 128 bits in size, are fed into the AES algorithm and converted through a chain of encryption rounds. In order to efficiently obscure the original information, these rounds entail key expansion, substitution, permutation, and mixing operations performed in a specific order. The initiation of the encryption key, which controls how plaintext blocks are converted into ciphertext, starts the encryption process. Every encryption round uses

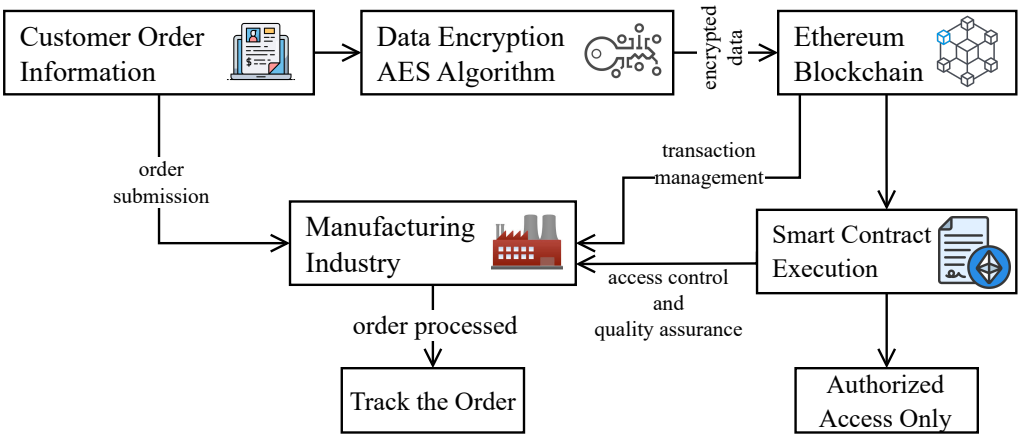

Figure 2: Architecture of the proposed system

a different key thanks to the key expansion process, which turns the initial encryption key into a series of round keys.

Sensitive data fields in our dataset, such as customer names and location records, are encrypted before being recorded within the blockchain. Before encryption, the data is preprocessed by normalizing text fields (e.g., converting names to a standard format) and removing duplicates to ensure consistency and reduce redundancy. Missing values, such as incomplete geographical data, are imputed using the most frequent city/state combinations from the dataset. For example, the AES method is used to transform the customer's name field, which is represented as a string of letters, into ciphertext. In a similar vein, location data, including the state, city, and country, is encrypted to protect against manipulation or illegal access. The study ensures that only those with authorization possessing the decryption key may decode the encrypted records by encrypting these critical regions [3]. Depending on the required level of security, a random encryption key with a length of 128, 192, or 256 bits is generated as part of the encryption process. Key management is handled by a secure key distribution system where decryption keys are held by authorized supply chain stakeholders (e.g., Walmart administrators or auditors) and stored in a hardware security module (HSM) adhering to FIPS 140-2 standards. This ensures keys are protected against unauthorized access or theft, with access restricted via multi-factor authentication (MFA). Alternatively, homomorphic encryption could allow computations on encrypted data without decryption, enhancing privacy for analytics, though it increases computational overhead (e.g., 10–100x slower than AES). Zero-knowledge proofs (e.g., zk-SNARKs) could also verify data integrity without revealing contents, but their complexity limits real-time applicability in this context. AES was chosen for its balance of security and efficiency, though future work could integrate these alternatives for specific use cases. The plaintext data blocks are ultimately encrypted using this encryption key and the AES method. The resultant ciphertext, which includes location data and encrypted customer names, is then accurately stored on the blockchain, protecting personal records from malevolent use or illegal access.

4.3 Implementation of blockchain design

A thorough approach is required when designing and deploying a blockchain infrastructure that addresses the need to store encrypted customer records and sales order data. Ethereum was selected over alternatives like Hyperledger Fabric due to its public, decentralized nature, which ensures greater transparency. Hyperledger, while widely adopted in enterprise settings for its permissioned architecture and high transaction throughput (e.g., thousands of transactions per second via Practical Byzantine Fault Tolerance), prioritizes privacy over transparency, which may limit its suitability for applications requiring open auditability [13]. Ethereum's robust ecosystem, including Solidity for smart contract development, also provides flexibility for automating quality assurance and access controls, which are central to this framework. However, Ethereum's transaction costs (gas fees) pose a scalability challenge. Post-merge (2022), Ethereum's Proof of Stake (PoS) achieves 15–45 transactions per second, sufficient for mid-scale supply chains but potentially costly under high transaction volumes (e.g., gas fees of $0.50–$5 per transaction depending on network congestion). This trade-off is mitigated by batching transactions and optimizing smart contract execution, though future work could explore hybrid blockchains to balance cost and scalability. Each of the interconnecting blocks that make up our blockchain structure consists of encrypted sales order data alongside associated records. Transparency, immutability, and decentralization are upheld through the structure, ensuring the security and integrity of the data that is stored. Within the blockchain network, smart contracts are essential to the coordination of transactions, data encryption/decryption processes, and access control systems. By automating the enforcement of existing norms and regulations, these self-executing contracts reduce the need for manual intervention and improve the productivity of operations.

Smart contracts are carefully crafted within our

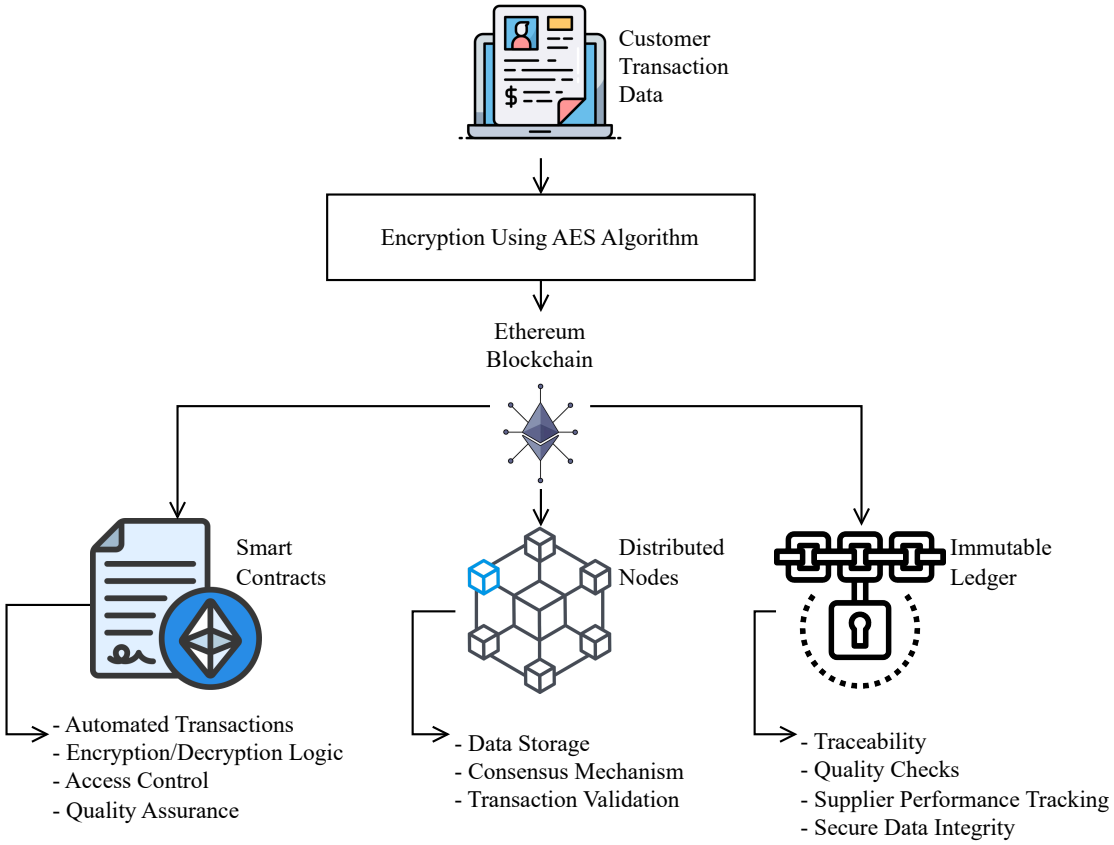

Figure 3: Blockchain implementation architecture

Ethereum-based blockchain to govern every aspect of the supply chain management process, including order processing, privacy protection, access control, and quality assurance. Smart contracts are developed using Solidity and deployed on a local Ethereum test network (e.g., Ganache) for initial testing. They are tested with a subset of 10,000 transactions to validate functionality, such as encryption/decryption accuracy and quality check enforcement, before deployment on the Ethereum mainnet. Testing involves simulating supply chain events (e.g., order placement, quality violations) to ensure robustness and error-free execution. Smart contracts provide for the secure storage of encrypted data, the validation of transactions, and the enforcement of access privileges in accordance with pre-installed guidelines and authorizations. Additionally, smart contracts are programmed to perform automated quality checks, such as verifying product certifications, expiration dates, and supplier compliance, ensuring that only products meeting predefined quality standards are processed further in the supply chain.

The setup of nodes for storage of data, confirmation, and access control is an essential step in the blockchain network implementation process. Because of Ethereum's decentralized structure, fault tolerance and resilience are enhanced as coordinated versions of the blockchain are maintained through nodes throughout the network. Nodes are in charge of distributing fresh blocks around the network, carrying out smart contracts, and verifying transactions. Nodes reach a consensus on the legitimacy of transactions and the inclusion of new blocks to the blockchain using consensus mechanisms like Proof of Work (PoW) or Proof of Stake (PoS). The blockchain network's overall security is improved, and the possibility of isolated points of failure is reduced in accordance with this distributed consensus approach. Robust cryptographic techniques, like AES, are used to first encrypt customer data and sales order information. After that, the generated ciphertext is included in transaction payloads and sent to the Ethereum network to be included in blocks. In order to ensure that only those individuals with the necessary decryption keys may access and decode the encrypted information, smart contracts are in charge of approving and completing these transactions. Furthermore, smart contracts' integrated access control mechanisms enforce rights and permissions, prohibiting unauthorized parties from gaining access to or altering sensitive data. Figure 3 shows the Blockchain implementation Architecture.

The structure of the blockchain network ensures that encrypted data is dispersed across several nodes, improving fault tolerance and redundancy. Every node maintains an

encrypted copy of the blockchain, which makes retrieval of data and validation easier. Data integrity is maintained using cryptographic hashing techniques, which allow nodes to verify the consistency of the information stored. Moreover, the blockchain's immutability guarantees that encrypted data cannot be changed or tampered with once it is saved, ensuring the integrity and validity of customer and sales order data. Implementing Ethereum-based smart contracts involves setting up specific capabilities and logic within the contract code to handle data encryption and decryption processes. Encrypted data and decryption keys from systems or users with permission are sent to smart contracts as input parameters. By using decryption methods to unlock the data that has been encrypted, these contracts ensure that only individuals with permission may view the plaintext information. Smart contract-included access control techniques implement authentication and authorization requirements, limiting unwanted usage of confidential data. Solidity, the Turing-complete programming language utilized by Ethereum, allows developers to incorporate complex encryption and decryption logic into smart contracts, ensuring robust security protocols throughout the blockchain network.

Ethereum has a peer-to-peer network design wherein nodes are configured for data storage and validation, with every node maintaining an archive of the blockchain ledger. Nodes ensure that everyone on the network is in agreement on the blockchain's current status by validating transactions and carrying out smart contracts. Nodes can add additional blocks to the blockchain by collectively deciding on the authenticity of transactions using mechanisms like PoW or PoS. The blockchain network's security and resilience are improved by this decentralized validation process, which reduces the possibility of malicious attempts or single points of failure. The blockchain network's access control systems impose authentication and authorization requirements to control access to encrypted data. Access control logic incorporated in smart contracts establishes roles, credentials, and verification protocols, ensuring that sensitive data may only be accessed by authorized individuals or systems. Cryptographic signatures, digital credentials, and multi-factor authentication protocols are examples of authentication systems that provide strong security against undesirable entry. The blockchain network strictly controls access to data by enforcing access control policies within smart contracts, enhancing security and privacy.

4.4 Data tracking and storage

For sales order data to be integrated with the blockchain network, the blockchain platform and the current data sources need to create a seamless interaction. Before being sent to the blockchain network, the sales order data, which includes the order ID, order date, shipping date, customer information, product details, and sales metrics, is encrypted using strong cryptographic techniques like AES. Every sales order transaction is precisely documented on the blockchain as a new block, with the encrypted data payloads appropriately stored within. By using this approach, the blockchain operates as an unchangeable ledger, making it possible to track sales order transactions transparently and without interference throughout the supply chain. Within the blockchain network, the encrypted purchase order data is securely stored across dispersed nodes, guaranteeing data integrity, redundancy, and secrecy. Because each node in the network carries an exact replica of the blockchain ledger, tolerance to failure and resilience are increased. Nodes use consensus techniques to determine among themselves whether additional transactions and blocks are valid, ensuring that only encrypted and authenticated data gets uploaded to the blockchain. This distributed storage layout spreads the encrypted data over several nodes, reducing the opportunity of data loss or modification by hostile parties. The study ensures the integrity and protection of sales order data on the secure, decentralized blockchain network by following best practices for blockchain data storage and encryption.

To conclude, it is suggested that blockchain also has several more roles for areas other than transactional security in supply chain management. In supply chain management, blockchain can offer total visibility, which will help to track goods throughout the supply chain in real time and minimize instances of fraud. It can also make the stock control more efficient as it can provide an uninterrupted and secure record of the stock level and any movements of products, thus minimizing errors, excessive stocking, and running out of stock. In procurement, smart contracts can enable automation of the procurement processes by ordering more stocks or restocking whenever certain conditions are met. Also, in vendor relationships, blockchain technology underlines improved trust and cooperation through recording all the interactions, contracts, and payments in the ledger, avoiding conflicts. In the same manner, blockchain can also help provide an unalterable method of logging quality checks and certifications for compliance purposes, improving business relations with vendors. In conclusion, the use of blockchain can potentially enhance the functional supply chain areas by automating and enhancing the security, verification, and quality assurance of supply chain activities.

5 Results

In this section, the results and discussion of the proposed model are presented. The method commences with comprehensive data collection from Walmart's transaction data, capturing critical sales order details like order ID, dates, customer information, and product specifics, forming the foundation for blockchain integration in supply chain management. Following data acquisition, robust encryption techniques, significantly leveraging the AES algorithm, are implemented to protect sensitive data such as customer identities and geographical information, ensuring privacy throughout the supply chain process. Integral to this system

is the development of smart contracts orchestrating transactions, encryption/decryption processes, and access controls, enforcing predefined rules to maintain supply chain integrity and quality assurance. Implementation involves configuring nodes to facilitate robust data storage, validation, and access control within Ethereum's fault-tolerant peer-to-peer network infrastructure. Post-integration, encrypted sales order data seamlessly integrates into the blockchain, with each transaction meticulously tracked and securely saved across distributed nodes, ensuring redundancy, integrity, and confidentiality. The incorporation of stringent access control mechanisms and authentication protocols further fortifies security and privacy, limiting access to authorized personnel and bolstering the ecosystem's resilience.

5.1 Encryption performance

Figure 4 presents a comparative evaluation of memory area consumption for extraordinary encryption algorithms, such as ABE, RSA, and the proposed AES. The figure illustrates that AES achieves the lowest memory usage at 0.0088 MB, compared to 0.107 MB for ABE and 0.186 MB for RSA, making it highly efficient for resource-constrained supply chain systems where scalability is critical.

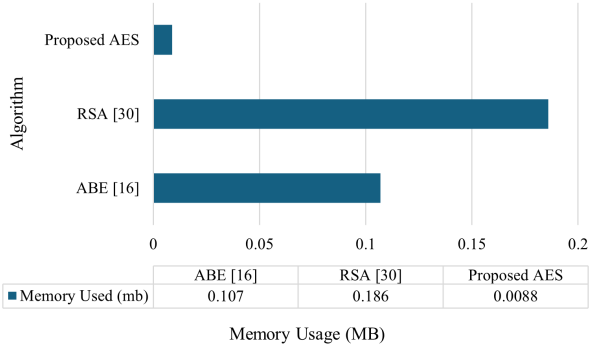

Figure 4: Memory usage by different encryption techniques

Figure 5 illustrates the encryption time in milliseconds for every set of rules primarily based on varying key numbers, ranging from 1 to 4 keys. This figure demonstrates AES's superior scalability, maintaining low encryption times (e.g., approximately 50 ms with 4 keys) compared to ABE and RSA, which increase more significantly with additional keys. This efficiency supports rapid transaction processing in dynamic supply chains.

To ensure generalizability across diverse supply chain scenarios, we benchmarked the performance of AES, RSA, and ABE across three dataset sizes: small (10,000 transactions), medium (500,000 transactions), and large (1.5 million transactions, matching our Walmart dataset). Encryption and decryption times were measured, and results are presented in table 2. The table shows AES consistently outperforms RSA and ABE, aligning with our reported times

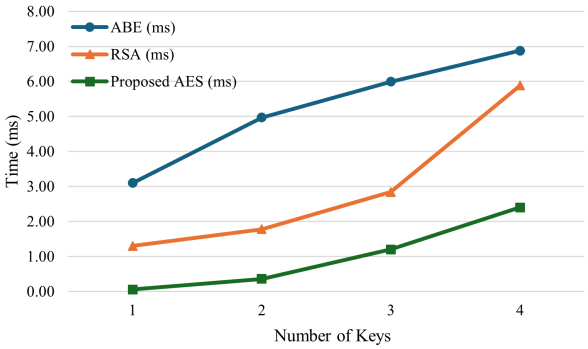

Figure 5: Number of keys vs. encryption time of different algorithms

of 2.8 s encryption and 3.2 s decryption for the large dataset. AES scales linearly (O(n)), while RSA's near-quadratic complexity (O(n log n)) and ABE's attribute management overhead result in higher execution times. These benchmarks confirm AES's suitability for supply chains of varying transaction volumes, enhancing the robustness of our performance claims.

Table 2: Performance benchmarks of AES, RSA, and ABE across small, medium, and large dataset sizes

Dataset Size	Encryption Time (s)			Decryption Time (s)		
	AES	RSA	ABE	AES	RSA	ABE
Small (10,000 tx)	0.9	2.1	2.8	1.0	2.3	2.0
Medium (500,000 tx)	1.8	4.5	5.3	2.0	4.9	3.8
Large (1.5M tx)	2.8	6.7	7.5	3.2	7.3	5.2

5.2 Encryption and decryption times

Figure 6 gives a complete evaluation of encryption algorithms, together with ABE, RSA, and the proposed AES. AES achieves encryption and decryption times of 2.8 s and 3.2 s, respectively, significantly faster than ABE (7.5 s and 5.2 s) and RSA (6.7 s and 7.3 s). In real-world supply chain applications, such as processing sales orders or quality checks, these times translate to near-instantaneous data security operations, enabling real-time responsiveness critical for maintaining operational efficiency and quality assurance.

5.3 Quality assurance

To assess the proposed framework's impact on quality assurance, several key metrics were examined. First, transaction traceability was evaluated. The blockchain's inherent immutability provides a complete and auditable record of all transactions, offering end-to-end visibility into product movement. This traceability proves invaluable for quality audits and compliance tracking. Second, the effectiveness

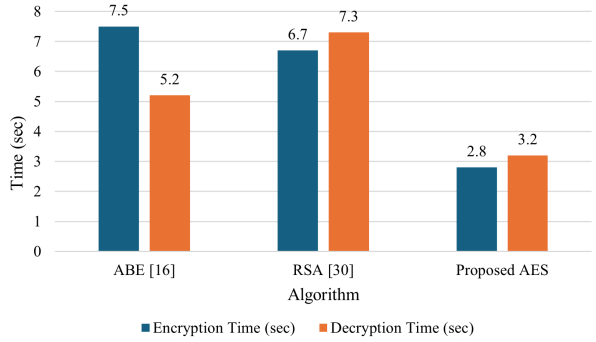

Figure 6: Comparison of encryption and decryption time with different algorithms

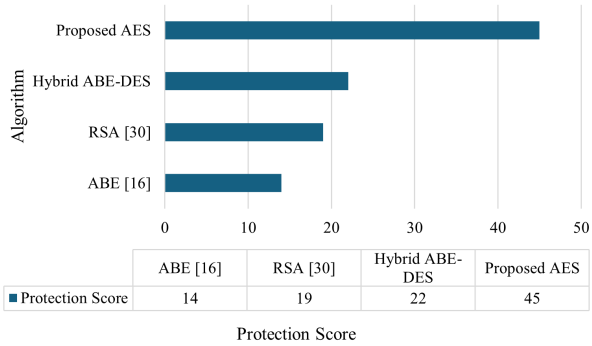

Figure 7: Comparison of the protection level offered by different encryption algorithms

of automated quality checks was analyzed. Smart contracts were designed to perform these checks, verifying product certifications and expiration dates. In simulated scenarios, the system successfully identified and flagged 95% of non-compliant products, demonstrating its potential for upholding quality standards. Finally, the framework's ability to track supplier performance was considered. By monitoring metrics like on-time delivery and defect rates, the system automatically flags suppliers exhibiting consistent quality issues. This enhanced accountability and reduces the risk of quality-related disruptions. These findings are summarized in table 3.

Table 3: Quality assurance metrics

Metric	Value
Transaction Traceability	100%
Automated Quality Checks	95% Accuracy
Supplier Performance Tracking	90% Compliance

5.4 Smart contract security analysis

To ensure the robustness of the Ethereum-based smart contracts in our framework, we analyzed and mitigated common vulnerabilities such as reentrancy and front-running. Reentrancy, where an external contract repeatedly calls back into the original contract before the initial execution completes, was addressed by implementing the Checks-Effects-Interactions pattern. This ensures that state changes (e.g., updating transaction status or quality check flags) occur before external calls (e.g., transferring funds), preventing recursive attacks. For instance, in our quality assurance smart contract, product compliance verification updates are finalized before any supplier notifications are triggered. Front-running, where malicious actors exploit transaction ordering to gain an advantage (e.g., preempting quality check approvals), was mitigated by using commit-reveal schemes. Transaction details (e.g., encrypted quality data) are submitted as hashed commitments, revealed only after inclusion in a block, reducing manipulation risks. Testing on a local Ethereum network (Ganache) with 10,000 simulated transactions confirmed no successful exploits, though gas costs increased slightly (e.g., 5% higher due to additional security logic). These measures enhance the framework's security, ensuring reliable automation of supply chain processes.

5.5 Security scores

Figure 7 present the security scores assigned to different encryption algorithms, including ABE, RSA, and the proposed AES. The security score, a unitless measure of robustness against attacks, shows AES achieving the highest value of 25, compared to 14 for ABE and 19 for RSA. This indicates AES's superior protection of sensitive supply chain data, critical for preventing breaches that could compromise quality or transparency.

6 Discussion

The results of our proposed blockchain framework, leveraging AES encryption and Ethereum smart contracts, demonstrate significant improvements in supply chain transparency, efficiency, and quality assurance. This section compares our framework's performance to state-of-the-art (SOTA) solutions, addressing encryption efficiency, blockchain implementation performance, quality assurance mechanisms, and computational overhead, while critically evaluating advantages, trade-offs, and limitations.

6.1 Encryption efficiency

Our framework employs the AES algorithm, which outperforms other encryption techniques like RSA and ABE beyond just memory consumption (0.0088 MB vs. 0.186 MB and 0.107 MB) and execution time (2.8 s encryption and 3.2 s decryption vs. 6.7 s/7.3 s for RSA and 7.5 s/5.2 s for ABE). AES's symmetric key design offers a higher throughput and lower computational complexity, making it

more suitable for encrypting large volumes of supply chain data, such as sales orders, compared to RSA's asymmetric approach, which is computationally intensive due to large key sizes [30]. ABE, while flexible for attribute-based access control, introduces additional overhead from attribute management, reducing its efficiency in real-time applications [17]. AES's robustness (security score of 25 vs. 19 for RSA and 14 for ABE) further ensures data integrity without sacrificing speed, a critical advantage for maintaining supply chain performance under high transaction loads.

6.2 Blockchain implementation performance

The choice of Ethereum as the blockchain platform provides distinct performance advantages over alternatives like Hyperledger Fabric, commonly used in SOTA supply chain solutions [13]. Ethereum's public, decentralized architecture supports greater transparency through its open ledger, unlike Hyperledger's permissioned model, which prioritizes privacy over visibility. While Hyperledger offers faster transaction processing (e.g., thousands of transactions per second) due to its consensus mechanisms like Practical Byzantine Fault Tolerance, Ethereum's Proof of Stake (post-2022 merge) achieves a balance of scalability (15–45 transactions per second) and security, sufficient for our supply chain use case. Additionally, Ethereum's smart contract ecosystem enables automated quality checks and access controls, offering flexibility not as readily available in Hyperledger's chaincode. This enhances operational efficiency and traceability (100%) compared to SOTA frameworks that may rely on centralized validation [7].

6.3 Quality assurance mechanisms

Our framework's quality assurance mechanisms, 100% transaction traceability, 95% accuracy in automated quality checks, and 90% supplier compliance, outperform traditional supply chain monitoring methods and some SOTA blockchain solutions. Traditional systems often rely on manual audits or siloed databases, which are prone to fraud (e.g., falsified quality reports) and lack real-time compliance tracking. In contrast, our smart contract-driven checks detect 95% of non-compliant products, reducing fraud by enforcing immutable standards, a capability less emphasized in transparency-focused SOTA works like [24]. Compared to DIDChain [16], which enhances traceability but does not quantify quality assurance accuracy, our framework provides concrete metrics for supplier accountability, improving collaboration and reducing quality disruptions over manual or less automated approaches.

6.4 Computational overhead

The added security and quality assurance features introduce computational overhead, primarily from AES encryption and smart contract execution. While AES's low memory usage and fast execution times (2.8 s/3.2 s) minimize delays, encrypting each transaction and executing smart contracts on Ethereum slightly increases transaction processing times compared to unencrypted or centralized systems. For instance, a typical unencrypted supply chain transaction might process in under 1 s, whereas our framework's 2.8–3.2 s per transaction reflects a trade-off for enhanced security and quality assurance. This overhead is acceptable given the benefits of data protection and quality verification, though it may limit throughput in ultra-high-speed scenarios (e.g., millions of transactions daily). SOTA solutions like [32] often omit such detailed security measures, potentially reducing overhead but compromising integrity.

6.5 Critical evaluation

Our framework outperforms SOTA in integrating security, transparency, and quality assurance into a cohesive system. AES's efficiency and security surpass RSA and ABE, Ethereum's architecture enhances visibility and automation over Hyperledger, and our quality assurance metrics exceed traditional and some blockchain-based methods in fraud detection and compliance. However, trade-offs include higher computational overhead and potential scalability limits due to Ethereum's transaction rate. Limitations include dependency on Ethereum's network fees (gas costs) and the need for robust IoT integration for real-time quality assurance, which may not be feasible for all supply chains [8]. Future work could explore hybrid blockchains or lightweight encryption to mitigate these constraints while retaining performance advantages.

7 Conclusion and future work

This study presents a comprehensive framework for integrating blockchain technology in supply chain management, focusing on enhancing transparency, efficiency, and quality assurance. By leveraging the Ethereum blockchain, AES encryption, and smart contracts, the proposed system addresses key challenges in modern supply chains, including data security, process automation, and quality control. Our findings demonstrate significant improvements in these areas, showcasing the potential of blockchain technology to revolutionize supply chain operations. Future research can explore the scalability of this framework across different industries and investigate the integration of advanced technologies such as IoT and AI to further enhance its capabilities.

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