Blockchain-Powered Security and Transparency in Supply Chain: Exploring Traceability and Authenticity through Smart Contracts

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ABSTRACT
Blockchain technology has emerged as a revolutionary force in reshaping supply chain management, providing innovative solutions to age-old security, transparency, traceability, and authenticity challenges. This research paper delves into the intricate relationship between blockchain technology and supply chain management, specifically emphasizing its role in enhancing traceability and ensuring authenticity, particularly in the context of smart contracts. Through the decentralized and secure storage of data in an immutable ledger, blockchain technology transforms supply chain operations, effectively mitigating risks and fostering accountability. This paper, informed by a comprehensive literature review and real-world case studies, illustrates the myriad applications and tangible benefits of blockchain technology in supply chain management, focusing on the traceability and authenticity of smart contracts. By exploring the critical role of blockchain in enhancing traceability, the research demonstrates how it enables end-to-end visibility into the movement of goods. Moreover, the paper investigates how blockchain ensures the authenticity of smart contracts by creating tamper-resistant and verifiable digital records. The findings underscore the considerable advancements in supply chain security and transparency achieved through blockchain adoption, specifically in the domain of smart contracts. This paper contributes to a nuanced understanding of the transformative power of blockchain in the realm of supply chain management, with a specific focus on the traceability and authenticity of smart contracts. It highlights the potential of blockchain technology to shape the future of global trade, providing a foundation for further exploration and implementation in the evolving landscape of supply chain dynamics.

General Terms
This research paper explores the transformative impact of blockchain technology on supply chain management, with a particular emphasis on its role in improving traceability and ensuring the authenticity of smart contracts. By leveraging decentralized and secure data storage in an immutable ledger, blockchain revolutionizes supply chain operations, addressing longstanding challenges related to security, transparency, traceability, and authenticity.

Keywords
Blockchain Technology, Supply Chain Management (SCM), Security, Authenticity, Traceability, Smart Contracts, Immutable Ledger.

1. INTRODUCTION
In an era characterized by globalized trade and complex manufacturing processes, the management of supply chains has become not only crucial but also increasingly intricate. The effectiveness of supply chain management (SCM) is instrumental in ensuring that goods and services are delivered to consumers efficiently and with minimal disruptions. This importance lies not only in the context of businesses striving for competitiveness but also in the broader perspective of economic sustainability and consumer well-being.

Yet, the modern supply chain landscape is fraught with a multitude of challenges that have persisted despite advancements in technology and logistics. Key among these challenges are the imperatives of security, transparency, traceability, and authenticity. The traditional, centralized models of supply chain management, although once groundbreaking, have exhibited limitations in addressing these challenges adequately. The vulnerabilities in security, the opacity in transactions, the lack of end-to-end traceability, and the ever-looming specter of counterfeit products compromise the integrity and efficiency of supply chains [1].

It is against this backdrop that this research endeavors to explore the transformative potential of blockchain technology in the realm of supply chain management. Blockchain, known for its decentralized, tamper-proof ledger, offers a novel approach to addressing these challenges. By providing a secure and transparent platform for recording and verifying transactions, blockchain technology presents an opportunity to revolutionize the way supply chains operate.

The core objectives of this research are to elucidate the role of blockchain technology in enhancing the security, transparency, traceability, and authenticity of supply chains. The authors will delve into the theoretical underpinnings of blockchain technology and its practical applications within the supply chain context. Through an examination of real-world case studies and a comprehensive review of existing literature, The authors aim to provide insights into how blockchain is reshaping supply chain management practices and the broader implications for businesses, consumers, and the global economy. As authors embark on this exploration, the significance of this research becomes apparent – it holds the potential to not only address persistent challenges but also redefine the future of supply chain management in an increasingly interconnected world [2].

2. LITERATURE REVIEW
To appreciate the significance of blockchain in supply chain management, it is essential first to understand the evolving landscape of supply chain management (SCM). SCM has long been recognized as a critical component of business operations, involving the planning, control, and optimization of material, information, and financial flows across the supply chain. The

integration of global markets, the emergence of e-commerce, and the ever-increasing customer expectations have made SCM more complex and vital.

In the literature, supply chain management is consistently described as a multifaceted process that requires coordination among various stakeholders, including suppliers, manufacturers, distributors, and retailers. It has been acknowledged that an effective SCM strategy can lead to cost reductions, improved customer service, and enhanced competitiveness. However, it is also apparent that traditional SCM systems often fall short in addressing the contemporary challenges that have arisen [3].

Blockchain technology, which originally gained prominence as the underlying technology for cryptocurrencies, has garnered substantial attention for its potential to disrupt various industries, including supply chain management. The blockchain is a distributed ledger technology that relies on a decentralized network of nodes to record and verify transactions. It is characterized by its immutability, transparency, and security features, making it an appealing solution for mitigating the challenges that have long plagued SCM.

The literature on blockchain underscores its ability to facilitate trust among parties, eliminate the need for intermediaries, and create an indelible record of transactions. These attributes have led to blockchain being described as a promising technology for enhancing transparency and security in various domains. Its applicability in SCM arises from the potential to enhance traceability, security, and authenticity, addressing limitations in traditional supply chain systems.

Traditional supply chain systems have demonstrated certain limitations that have fueled the exploration of alternative technologies such as blockchain. Among the prominent challenges are security concerns, particularly in the age of cyber threats and data breaches. The centralized nature of traditional SCM systems has made them susceptible to attacks and unauthorized access.

Moreover, the lack of transparency in these systems has been a longstanding issue. Participants in a supply chain often have limited visibility into the actions of other stakeholders, resulting in information silos and difficulties in tracking the flow of goods and data. This opacity can lead to inefficiencies, delays, and a lack of accountability [4].

Additionally, traceability and authenticity have been elusive goals in traditional supply chains, contributing to issues related to provenance and the presence of counterfeit products. Traditional systems often rely on paper-based documentation, which is susceptible to fraud and errors.

These challenges, well-documented in the existing literature, underscore the need for innovative solutions in supply chain management. Blockchain technology emerges as a viable candidate to address these limitations, as it promises to offer a decentralized, transparent, and secure alternative to traditional SCM systems.

The existing literature on the topic of how blockchain technology enhances the security and transparency of supply chain management, with a focus on traceability and authenticity. The authors will provide a summary of relevant findings from existing papers:

"Blockchain Technology and Supply Chain Management: A Review" by Iqbal and Khan (2019)"

- This paper provides an in-depth review of how blockchain technology can be leveraged to address challenges in supply chain management. It emphasizes that blockchain's decentralized ledger can enhance security by reducing the risk of fraudulent activities and unauthorized access in the supply chain. Additionally, it highlights the potential for blockchain to enhance transparency and traceability by creating an immutable record of transactions [5].

"Research on agricultural supply chain system with double chain architecture based on blockchain technology" by Leng et al. (2018)"

- Leng and his colleagues examine the challenges faced by traditional supply chain systems and how blockchain technology can offer solutions. The paper discusses how blockchain's decentralized and tamper-proof ledger can ensure the authenticity of products by recording their entire journey through the supply chain. It also emphasizes the role of blockchain in enhancing traceability by providing stakeholders with real-time visibility into the movement of goods [6].

"Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors" by Bass et al. (2018)"

- Bass and his team focus on the critical aspect of traceability in supply chains. The paper highlights the importance of traceability for ensuring product authenticity and discusses how blockchain can serve as a powerful tool to achieve this. It provides insights into the business requirements and critical success factors when implementing blockchain for traceability [7].

"The Impact of Blockchain Technology on Business Models in the Supply Chain: A Systematic Literature Review" by Hackius and Petersen (2017)"

- This systematic literature review delves into the transformative potential of blockchain in supply chain management. It explores how blockchain can enhance transparency and security by eliminating information silos and intermediaries. The review also highlights the significance of blockchain in ensuring the authenticity of products and improving traceability [8].

"Blockchain Technology in the Supply Chain: Benefits and Future Challenges" by Zheng et al. (2020)"

- This paper examines the benefits and challenges of applying blockchain technology to supply chain management. It discusses how blockchain can enhance transparency and traceability by creating a shared ledger accessible to all participants. It also underscores the potential to verify the authenticity of products using blockchain [9].

These existing papers collectively underscore the transformative potential of blockchain technology in addressing the security, transparency, traceability, and authenticity challenges in supply chain management. They provide a foundation for further research and emphasize the need to explore real-world applications and case studies to fully understand the impact of blockchain in supply chain contexts.

2. BLOCKCHAIN TECHNOLOGY IN SUPPLY CHAIN MANAGEMENT

Blockchain technology is a decentralized and distributed ledger system that underlies cryptocurrencies like Bitcoin. It's known for its transparency, security, and the elimination of central authorities.

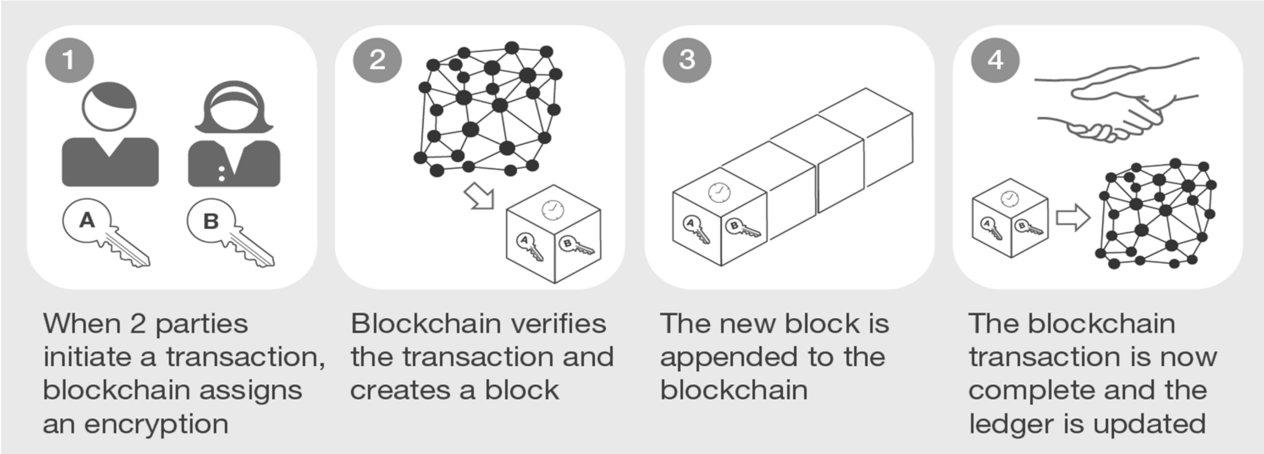

Fig. 1. Blockchain Technology for Supply Chains

Let's break down the fundamentals of blockchain technology, including decentralized ledgers, smart contracts, and consensus mechanisms:

3.1 Decentralized Ledgers

A blockchain is a digital ledger or database that records a series of transactions. Unlike traditional centralized databases, blockchain is decentralized, meaning it is not stored on a single central server or controlled by a single entity.

Instead, copies of the blockchain ledger are stored on a vast network of computers (nodes) that are distributed worldwide. Each node has an identical copy of the ledger.

Decentralization enhances security, transparency, and immutability. It makes it extremely difficult for any single party to manipulate the data or control the entire network.

3.2 Smart Contracts

Smart contracts are self-executing contracts with the terms of the agreement directly written into code. They automatically execute and enforce the terms of the contract when predefined conditions are met. Smart contracts are a fundamental feature of some blockchain platforms, such as Ethereum. They can be used for a wide range of applications, including financial agreements, supply chain management, and even voting systems.

The code of a smart contract is stored on the blockchain, ensuring transparency and trust in the execution of contractual agreements without the need for intermediaries.

3.3 Consensus Mechanisms

Consensus mechanisms are protocols used in blockchain networks to achieve agreement among nodes on the validity of transactions and the order in which they are added to the blockchain.

The most well-known consensus mechanism is Proof of Work (PoW), used in Bitcoin. In PoW, miners compete to solve complex mathematical puzzles to validate transactions and create new blocks. The first miner to solve the puzzle adds a new block to the blockchain.

Another widely used consensus mechanism is Proof of Stake (PoS), which is used in cryptocurrencies like Ethereum 2.0. In PoS, validators are chosen to create new blocks and validate transactions based on the amount of cryptocurrency they "stake" as collateral.

Other consensus mechanisms include Delegated Proof of Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT), and more, each with its unique approach to achieving consensus [10].

3.4 The Potential Applications of Blockchain in Supply Chain Management

Blockchain technology holds significant promise in revolutionizing supply chain management by enhancing transparency, security, and efficiency in the flow of goods and information. Its potential applications in this domain are diverse and impactful.

One of the primary benefits of blockchain is the provision of enhanced transparency. By offering a shared, real-time ledger accessible to all stakeholders, it facilitates end-to-end visibility into the supply chain. This transparency allows for tracking the movement of goods, verifying product authenticity, and monitoring the performance of suppliers and logistics partners.

Blockchain's traceability features are another valuable asset. Each product or batch can be assigned a unique digital identity, recording information about its origin, manufacturing process, quality checks, and shipment details. This traceability empowers supply chain actors to swiftly identify the source of issues, whether they be related to contamination, defects, or theft [11].

The technology also plays a pivotal role in reducing the prevalence of counterfeit products. The immutable records created by blockchain make it difficult for counterfeit goods to infiltrate the supply chain. Customers and businesses can verify the authenticity of products by scanning a QR code or accessing the blockchain's product history.

Furthermore, blockchain's smart contracts streamline supply chain processes. These self-executing contracts with predefined rules can automate and optimize various operations, such as releasing payments to suppliers upon successful product delivery. This automation minimizes manual paperwork and delays.

Inventory management benefits from blockchain as well. Real-time tracking of inventory levels prevents overstocking or understocking, optimizing resource allocation and reducing costs. Additionally, blockchain can enhance supply chain financing by creating a secure and transparent digital ledger for trade finance, ultimately improving access to working capital for suppliers.

Ethical sourcing and sustainability efforts can also be strengthened through blockchain technology. Companies can trace the origin of raw materials, ensuring they come from ethical and sustainable sources. This transparency is especially critical in industries where consumers and regulators demand responsible sourcing practices [12].

In the unfortunate event of product recalls, blockchain enables quick and accurate identification of affected batches, thereby reducing the scope and cost of recalls and minimizing their impact on consumers and brand reputation.

Supplier management is another area where blockchain can bring transformative benefits. By creating a comprehensive supplier database with transparent records of performance, quality, and compliance, organizations can make more informed decisions and foster stronger relationships with reliable suppliers.

Customs processes and compliance verification are simplified through blockchain. The technology offers secure and transparent documentation, helping to verify compliance with trade regulations and reducing the risk of fraud.

Data security is paramount in supply chain management. Blockchain ensures data security through encryption and decentralized storage, safeguarding sensitive supply chain information from cyber threats and data breaches.

As blockchain technology matures and gains wider adoption, its potential to bring efficiency, security, and transparency to supply chain management becomes increasingly evident. These applications are actively being explored in various industries to reduce costs, mitigate risks, and meet the growing demands for ethical and sustainable sourcing, ultimately reshaping supply chain management practices fundamentally [13].

3.5 Blockchain: A Solution for Security and Transparency

Blockchain technology has the potential to address security and transparency issues in various industries, including supply chain management, financial services, healthcare, and more.

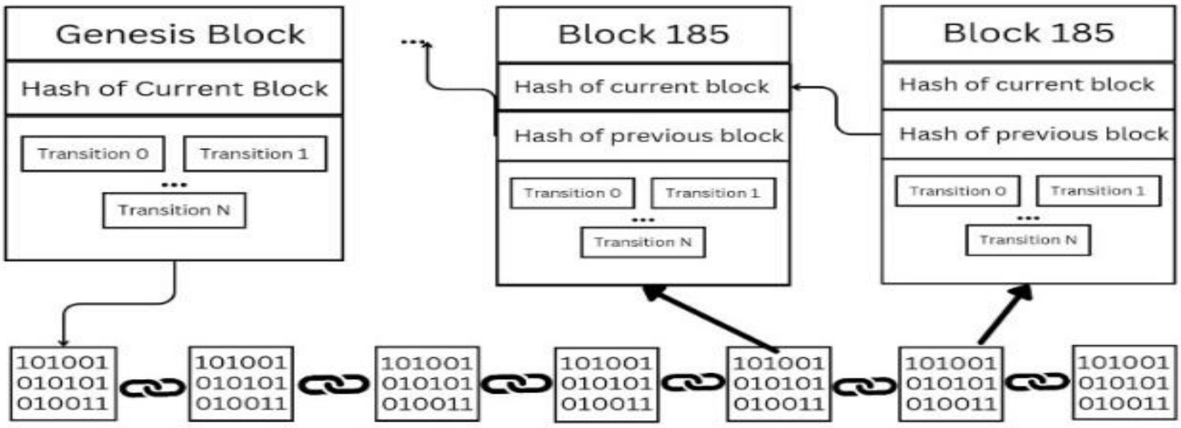

Fig. 2: The Architecture of a Data Chain in a Blockchain Network

Here's an exploration of how blockchain can provide solutions to these challenges:

3.5.1 Security

Immutability: Once data is recorded on the blockchain, it becomes nearly impossible to alter. Each block contains a reference to the previous block, and any change to the data in one block would require changing all subsequent blocks, which is computationally infeasible. This immutability enhances data security.

Decentralization: Blockchain operates on a decentralized network of computers (nodes). Data is not stored on a single server or controlled by a central authority. This distributed structure reduces the risk of a single point of failure and makes it more challenging for malicious actors to compromise the network.

Cryptography: Transactions on the blockchain are secured through cryptographic algorithms. Private keys provide access to users' digital assets, while public keys are used to verify the authenticity of transactions. This cryptographic layer enhances the security of data and digital assets.

Consensus Mechanisms: Blockchain uses consensus mechanisms like Proof of Work (PoW) or Proof of Stake (PoS) to validate and add transactions to the ledger. These mechanisms ensure that only valid and authorized transactions are added, reducing the risk of fraudulent activities [14].

3.5.2 Transparency

Shared Ledger: The blockchain ledger is visible to all participants in the network. This transparency means that all stakeholders can access the same data, reducing information silos and discrepancies.

Real-Time Updates: Changes to the blockchain are recorded in real-time and are immediately visible to all relevant parties. This feature allows for up-to-the-minute tracking and verification of transactions.

Public vs. Private Blockchains: Depending on the use case, organizations can choose between public or private blockchains. Public blockchains provide full transparency to anyone, while private blockchains restrict access to authorized participants. This flexibility allows organizations to balance transparency and privacy based on their specific needs [15].

Smart Contracts: Smart contracts are self-executing agreements with predefined rules. They automatically execute when conditions are met, ensuring that contractual terms are transparent and enforceable.

Audit Trails: The blockchain ledger provides a permanent and unchangeable audit trail of all transactions. This is crucial for regulatory compliance and dispute resolution.

Blockchain's ability to address both security and transparency challenges makes it a powerful tool in various sectors. In supply chain management, it ensures the authenticity of products, tracks goods in real-time, and reduces the risk of counterfeiting. In healthcare, it secures patient records and enhances data sharing. In finance, it provides secure and transparent transactions. The combination of security and transparency makes blockchain an attractive solution for businesses and industries seeking to improve their operations and build trust with stakeholders [16].

4. TRACEABILITY IN THE SUPPLY CHAIN

Traceability in the context of supply chains refers to the ability to track the movement and history of products or goods from their origin through every stage of production, processing, distribution, and delivery to the end consumer. It involves creating a detailed, transparent, and unbroken record of the journey a product takes within the supply chain. This information includes data about the product's source, manufacturing, quality checks, handling, and transportation.

Blockchain technology can greatly facilitate end-to-end traceability in supply chains. By leveraging blockchain, each product or batch can be assigned a unique digital identity or token. This digital identity is then recorded on the blockchain, forming an unchangeable and publicly accessible record of the product's entire history. Every stakeholder within the supply chain, from producers and manufacturers to distributors and retailers, can access and update this information in real-time [17].

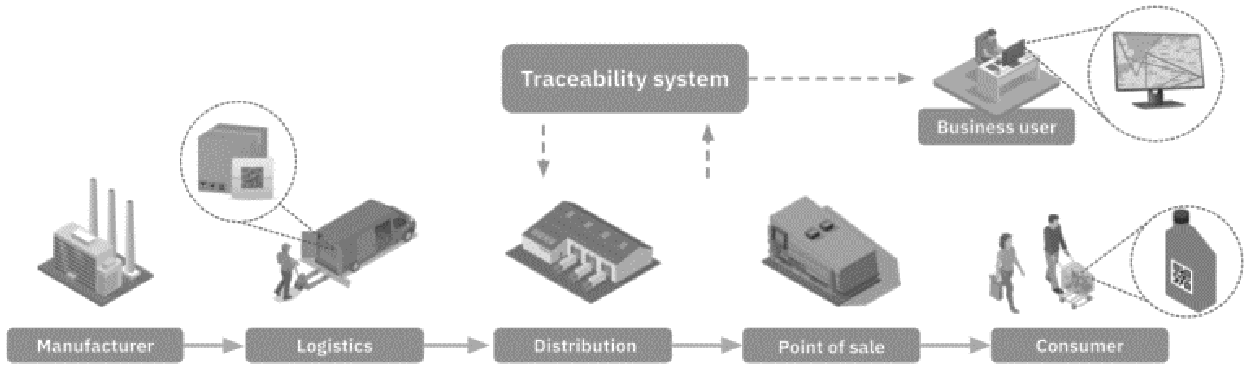

Fig. 3: Traceability Solutions for Supply Chains

This system ensures complete transparency and trust in the supply chain. Consumers can verify the authenticity and quality of products by scanning a QR code or accessing the blockchain's product history. In the event of recalls, blockchain enables quick and precise identification of affected batches, minimizing the scope and cost of the recall and ensuring the safety and satisfaction of consumers.

Real-world applications of blockchain for traceability are abundant. For instance, in the food industry, companies like Walmart and Nestlé have adopted blockchain to trace the origins of food products. In the diamond industry, De Beers uses blockchain to track the journey of diamonds from mines to consumers, ensuring they are conflict-free. Additionally, pharmaceutical companies are exploring blockchain to combat the proliferation of counterfeit drugs and enhance the traceability of medications.

Overall, blockchain's ability to create a transparent, immutable, and accessible ledger makes it a powerful tool for achieving end-to-end traceability in supply chains, ensuring product authenticity and quality while streamlining recall processes and compliance with regulations [18].

5. ENSURING AUTHENTICITY WITH BLOCKCHAIN IN SUPPLY CHAINS

5.1 Counterfeit Products and Ensuring Authenticity in Supply Chains

The issue of counterfeit products is a pervasive and persistent challenge in supply chains across various industries. Counterfeits not only lead to financial losses for companies but also pose significant risks to consumers' safety and the integrity of brands. Ensuring product authenticity is paramount, and blockchain technology offers a compelling solution to address this pressing concern.

5.2 Blockchain's Role in Verifying Product Authenticity

Blockchain, with its foundational features of immutability and transparency, can play a crucial role in verifying the authenticity of products. By creating unique digital identities for each product or batch and recording their entire journey on the blockchain, companies can establish an unchangeable and publicly accessible record. This digital identity includes essential information, such as the product's source, manufacturing processes, quality checks, handling, and transportation [19].

The immutability of blockchain is a game-changer. Once data is entered into the blockchain, it becomes nearly impossible to alter. This is because each block in the blockchain contains a cryptographic reference to the previous block, making any modification requires changing all subsequent blocks, which is a computationally infeasible task. This immutability ensures the security and authenticity of the product's history.

5.3 Real-World Applications of Blockchain to Combat Counterfeiting

Several case studies and examples demonstrate the efficacy of blockchain in combating counterfeiting:

Food Industry: Major players like Walmart and Nestlé have harnessed blockchain technology to trace the origins of food products. This not only ensures food safety and quality but also helps in swiftly identifying the source of contamination or quality issues.

Diamond Industry: De Beers, a prominent player in the diamond industry, utilizes blockchain to guarantee the authenticity and conflict-free status of diamonds. The immutable records on the blockchain assure consumers of the legitimacy of their purchases.

Pharmaceuticals: The pharmaceutical sector is increasingly adopting blockchain to combat the proliferation of counterfeit drugs. By allowing consumers to verify the authenticity of medications through blockchain, pharmaceutical companies enhance patient safety and ensure the quality of the drugs they produce.

These examples showcase the transformative potential of blockchain in enhancing transparency and trust within supply chains. Its capacity to create unchangeable, accessible, and comprehensive records of product histories provides a powerful tool for combatting counterfeits and assuring the authenticity of products, ultimately safeguarding consumers and the integrity of brands [20].

6. SECURITY AND TRANSPARENCY: BLOCKCHAIN'S DUAL ROLE IN SUPPLY CHAIN MANAGEMENT

Blockchain technology offers a comprehensive solution to enhance security and transparency in supply chains. Here's a brief analysis of how blockchain achieves this and a comparison with traditional supply chains:

6.1 Enhanced Security

Data Encryption: Blockchain employs cryptographic techniques to encrypt data, ensuring that sensitive information remains secure and inaccessible to unauthorized parties. This encryption adds an extra layer of security to transactions and data storage.

Access Control: Blockchain provides users with private keys to access their digital assets. Public keys are used to verify the authenticity of transactions. This access control mechanism ensures that only authorized individuals can interact with the blockchain, reducing the risk of unauthorized access and fraud [22].

Decentralized Verification: The decentralized nature of blockchain means that transactions and data are verified and stored on a distributed network of nodes. This decentralized verification makes it extremely difficult for a single entity to manipulate or control the entire network, enhancing data security.

6.2 Achieving Transparency

Distributed Ledger: Blockchain operates on a distributed ledger that is visible to all participants in the network. Every participant has an identical copy of the ledger, ensuring that information is shared among stakeholders. This distributed ledger minimizes information silos and fosters transparency.

Real-Time Updates: Changes to the blockchain are recorded in real-time, and this information is immediately accessible to all relevant parties. Real-time updates allow for up-to-the-minute tracking and verification of transactions, contributing to transparency.

6.3 Blockchain vs. Traditional Supply Chains

Security: Blockchain-based supply chains have a distinct advantage in terms of security. The combination of data encryption, access control, and decentralized verification significantly reduces the risk of data breaches and fraud. In traditional supply chains, data is often stored in centralized systems, making them more vulnerable to attacks and unauthorized access.

Transparency: Blockchain-based supply chains excel in transparency due to their distributed nature and public accessibility. Every stakeholder has access to the same, up-to-date information, reducing information disparities and enhancing trust. Traditional supply chains often involve fragmented data storage and a lack of real-time visibility, leading to reduced transparency and potential inefficiencies.

In summary, blockchain technology enhances security through data encryption, access control, and decentralized verification. It achieves transparency through its distributed ledger and real-time updates. When compared to traditional supply chains, blockchain-based supply chains offer superior security and transparency, reducing risks and inefficiencies in the process [21].

7. SMART CONTRACTS FOR TRACEABILITY IN SUPPLY CHAIN MANAGEMENT

To establish a robust product traceability process, this paper introduces the design of three essential smart contracts: the Product Registration Contract (PRC), the Batch Addition Contract (BAC), and the Transaction Update Contract (TUC). These contracts are interlinked, enhancing cooperation and ensuring a seamless flow of information. The structure involves the PRC containing addresses of BAC contracts, and BAC contracts containing addresses of TUC contracts, establishing a well-connected and cooperative framework.

To facilitate comprehension, the term "product" in this context encompasses both finished products and raw materials. The PRC contract, initiated by the system manager, assigns a unique BAC contract address to each registered product during the registration process, capturing vital production batch details. Subsequently, the BAC contract, deployed by the owner of each product, then assigns a unique TUC contract address to each production batch, updating the product's transfer process within that batch. Essentially, each product corresponds to a batch list, and each batch corresponds to a detailed product transfer process [23].

For end consumers seeking insight into the history of a purchased product, the ability to query transfer details by product code and batch number is facilitated. Additionally, each contract maintains an authorization list, ensuring that only authorized accounts possess the right to update the contract status. In the event of malicious activity, the regulator holds the highest authority to remove the user from the authorization list, ensuring system integrity.

7.1 Product Registration Contract (PRC)

The PRC contract, deployed by the system manager, features a product registration function named register(). This function permanently stores registration information for all products, including product code, product name, product owner, and raw materials. Upon registration, a BAC contract is automatically deployed at a new address, utilizing the owner's account, and the BAC contract address is added to the product registration information.

7.2 Batch Addition Contract (BAC)

Initiated by the product owner during product registration, the BAC contract provides the addBatch() function to incorporate production batch information permanently. Batch managers add details for each batch, including batch number, batch manager, timestamp, and the batch number of raw materials used. Simultaneously, a corresponding TUC contract is deployed.

7.3 Transaction Update Contract (TUC)

Deployed by the batch manager during batch addition, the TUC contract provides the updateTr() function to enhance the transaction history for the batch. Product senders initiate transactions, updating the transaction record with relevant information, including the hash of the current transaction, sender and recipient details, hash of the previous transaction, and timestamp. This meticulous process ensures the authenticity and legitimacy of each transaction, preventing disruptions in the product traceability process [24].

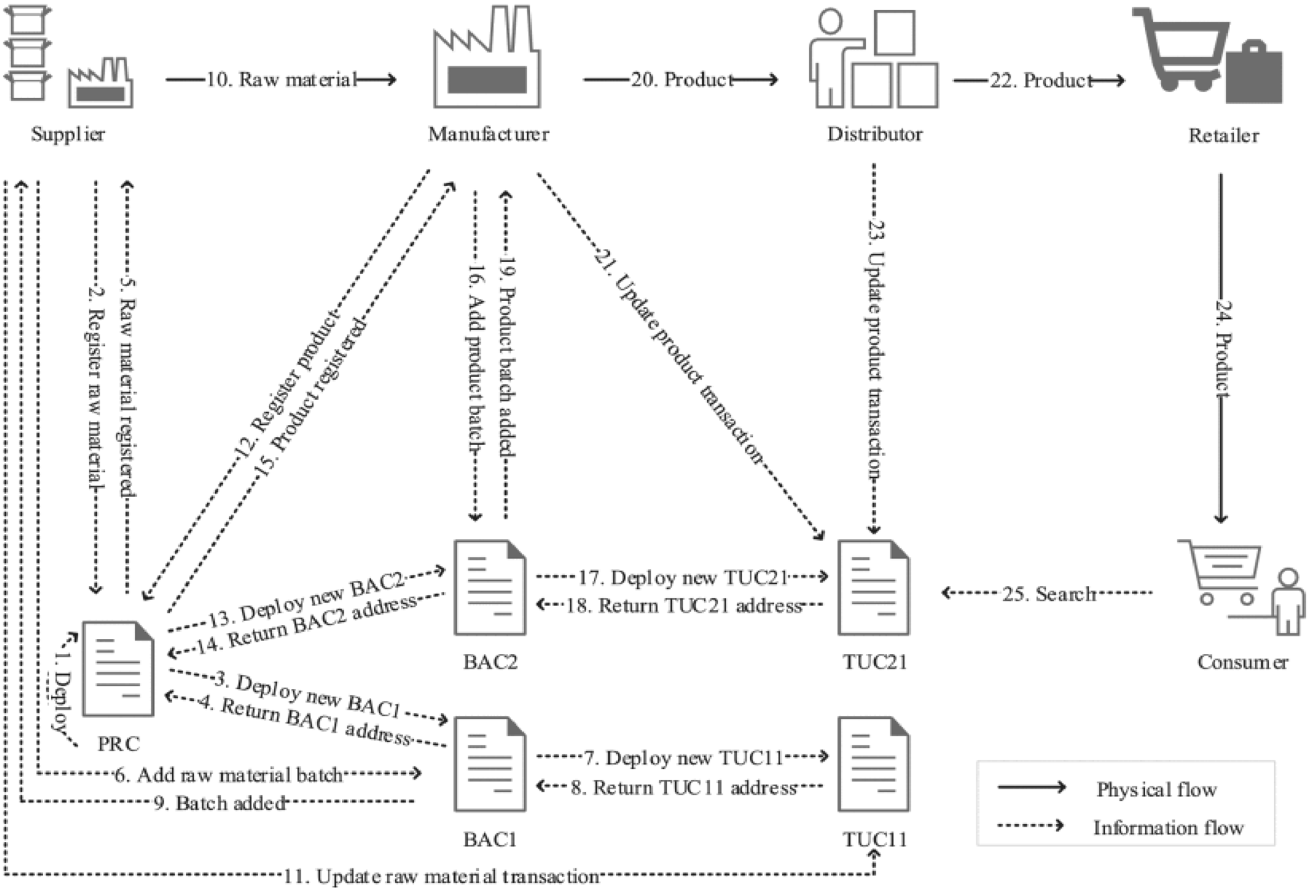

Fig. 4: Product Registration, Transfer, and Tracking Workflow

Illustrated in Figure 4, the product traceability process within the supply chain system encompasses several key stages, including contract deployment, raw material registration, raw material procurement, product registration, product distribution, product wholesale, product purchase, and product source querying. Each step is elucidated below:

7.3.1 Contract Deployment

At the onset (Step 1 in Figure 4), the system manager deploys the Product Registration Contract (PRC) to the blockchain, making the contract address public.

The deployment of the Batch Addition Contract (BAC) and the Transaction Update Contract (TUC) occurs automatically when the register() and addBatch() functions are invoked, respectively.

7.3.2 Raw Material Registration

Suppliers initiate the raw material registration process, inputting information on raw materials and production batches.

Table 1. Example of Product Information List in PRC

Contract

ID	Product Code	Product Name	Product Owner	Raw Materials	Timestamp	BAC Address
1	109735813	cocoa	0xc07…f0e4	/	1562065155	0xbcc0…d4c77
2	1654564413	milk	0x32c…d192	/	1562065206	0x5695…9209c
3	6928480334788	Coffee	0x69a…0013	109735813, 165456413	1562065276	0xa911…0ac5a
4	163113107	tea	0x38c…0d2a	/	1562065411	0xa145…0e6d4
…	…	…	…	…	…	…

The supplier leverages the register() function in the PRC contract to record raw material information (refer to Table 1).

Simultaneously, the supplier's account triggers the automatic deployment of a BAC1 contract, with its address added to the raw material registration information. After registering raw materials in batches, the supplier utilizes the addBatch() function in the corresponding BAC1 contract.

The execution of this function results in the automatic deployment of a TUC11 contract, with its address added to the batch information of the raw material. The system returns the registration and execution results to the supplier (Step 2–5 in Figure 4).

This meticulous raw material registration process ensures that both individual raw materials and batches are systematically recorded and linked to their respective contracts on the blockchain [25].

7.3.3 Raw Material Procurement

The raw material procurement process unfolds in a collaborative exchange between the supplier and the manufacturer. Once a mutual agreement is reached—comprising the supplier's confirmation of delivery and the manufacturer's confirmation of receipt—the subsequent step involves the supplier uploading transaction information (refer to Table 3) to the contract. This action is executed by invoking the updateTr() function within the TUC11 contract, as depicted in step 11 of Figure 4.

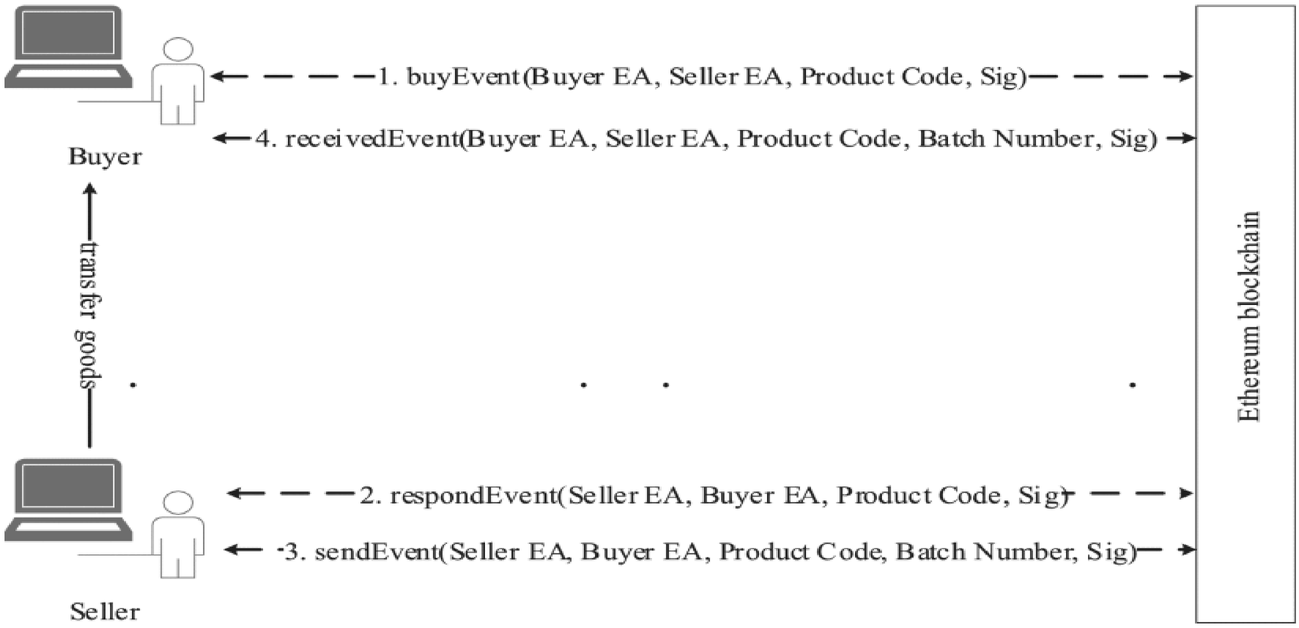

Fig. 5: Mechanism for Event Responses in Transaction Processes

A. Goods Transaction Process

As illustrated in Figure 5, the intricacies of the transaction agreement, encompassing the purchase request, confirmation, shipping, and receipt, are explicated. This process corresponds to step 10 in Figure 5 and is detailed below.

B. Purchase Request Initiation

The buyer initiates a purchase request, triggering the buyEvent() event.

Key information is included in this event: Buyer's Ethereum address (Buyer EA), Seller's Ethereum address (Seller EA), the Product Code of the item to be purchased, and the initiator's Ethereum account public key (EPK). A signature (Sig) is appended, signed with the initiator's account private key, ensuring the authenticity of the request and confirming the identity of both parties [26].

C. Event Response

The seller, upon receiving the purchase request, queries log records based on their Ethereum address. Verification of the signature within the event is conducted. If successful, the seller triggers the responseEvent() event. This event serves as a response to the buyer's request, creating a streamlined communication channel.

D. Goods Shipment Confirmation

After the response, the seller ships the goods to the buyer, triggering the sendEvent() event. The information included in this event comprises the Seller's Ethereum address (Seller EA), the Buyer's Ethereum address (Buyer EA), the Product Code, the Batch Number of the shipped goods, and the seller's Ethereum account public key (EPK). A signature (Sig) is appended, authenticated with the seller's account private key, providing proof of shipment.

E. Goods Receipt Confirmation

Upon receiving the goods, the buyer triggers the receivedEvent() event, certifying the successful receipt of the goods. This event solidifies the acknowledgment of the completion of the transaction and the receipt of the shipped items.

7.3.4 Manufacturer-Driven Transaction Processes

In the existing scenario, the manufacturer takes on the role of the buyer, and the supplier assumes the position of the seller. Upon the completion of the preceding process, the supplier diligently updates transaction information to the corresponding Transaction Update Contract (TUC) contract, specifically the TUC11 contract in Figure 2. The assumption here is that both transaction parties faithfully trigger the events described earlier, ensuring the accuracy of the updated transaction information and establishing the reliability of the product source.

A. Product Registration

The manufacturer spearheads the product registration process, encompassing both product and batch information registration. This process prompts the deployment of the Batch Addition Contract (BAC2) and the associated Transaction Update Contract (TUC21). Given the similarity to the raw material registration process, detailed steps for this are omitted, as depicted in steps 12–19 of Figure 4.

B. Product Distribution

The distribution of products unfolds collaboratively between the manufacturer and the distributor. Following a consensus, as delineated in the process illustrated in Figure 5, the manufacturer updates transaction information in the contract. This is achieved through the invocation of the updateTr() function within the TUC21 contract, as demonstrated in steps 20 and 21 of Figure 5.

C. Product Wholesale

The wholesale process, involving transactions between the distributor and the retailer, follows a similar consensus-building procedure outlined in Figure 5. The distributor, upon consensus, uploads transaction information to the contract using the updateTr() function in the TUC21 contract, detailed in steps 22 and 23 of Figure 4.

D. Product Purchase

Consumers, in the final stage, purchase products from retailers via supermarkets or hypermarkets, reaching step 24 of Figure 4. Due to the inherent uncertainty of consumer choices, transaction information is not preemptively uploaded to the blockchain in this step.

E. Product Source Querying

Consumers, having the option to join the network as either lightweight nodes or full nodes, can inquire about the entire transaction history of the purchased product using the product code and batch number. In step 25 of Figure 4, consumers input the product code and batch number, clicking the "OK" button on the page to view the product source. Importantly, this operation incurs no gas consumption [27].

8. CASE STUDY: BLOCKCHAIN REVOLUTIONIZING BANGLADESH'S TEXTILE SUPPLY CHAIN - ENSURING TRACEABILITY AND AUTHENTICITY

The textile industry in Bangladesh plays a pivotal role in the country's economy, known for its cost-effective production and quality textiles. However, challenges related to traceability and authenticity have persisted, with counterfeit products and labor issues being pressing concerns. In response to these challenges, blockchain technology has emerged as a game-changing solution, significantly enhancing traceability and authenticity in the textile supply chain [28].

8.1 Challenges in the Textile Supply Chain

Counterfeit Products: The textile industry in Bangladesh has faced the issue of counterfeit textiles, undermining consumer trust and the industry's reputation.

Ethical Sourcing and Labor Conditions: Ensuring ethical sourcing of materials and fair labor conditions has been a persistent challenge in the industry.

8.2 Blockchain Implementation

Several key stakeholders in the Bangladeshi textile industry have embraced blockchain technology to address these challenges:

Authenticity and Product Traceability

- **Digital Product Identities:** Each textile product is assigned a unique digital identity recorded on the blockchain. This identity includes comprehensive information about the product's origin, manufacturing process, quality checks, and transportation.
- **QR Code Verification:** Consumers can scan QR codes on product labels, granting them access to the blockchain's transparent product history. This verification allows consumers to confirm the authenticity and origin of their purchases [29].

Ethical Sourcing and Labor Conditions

Blockchain for Labor Records: Labor records of all workers in the textile supply chain, spanning from cotton farms to garment factories, are stored on the blockchain. This ensures adherence to ethical labor standards and fair compensation for workers.

Smart Contracts: Smart contracts automate wage payments to workers when predefined conditions are met. This mechanism promotes transparency and equity in wage distribution.

8.3 Transparency and Regulatory Compliance

Distributed Ledger: The blockchain ledger is accessible to all stakeholders in the textile supply chain, facilitating real-time transparency. Every participant has access to the same up-to-date information.

Blockchain for Regulatory Compliance: The blockchain system assists in meeting local and international regulatory requirements, ensuring that products adhere to safety and quality standards.

8.4 Results and Benefits

Mitigation of Counterfeit Products: The implementation of blockchain technology has substantially reduced the prevalence of counterfeit textiles. The easy verification of product authenticity empowers consumers and deters counterfeiters.

Improved Labor Conditions: Ethical labor practices have been significantly enhanced. The blockchain system ensures that labor standards meet international guidelines, and workers are fairly compensated.

Supply Chain Transparency: The textile supply chain now operates with unprecedented transparency. This transparency is instrumental in rapidly identifying and resolving issues.

Blockchain technology has played a transformative role in the Bangladesh textile industry, addressing the longstanding challenges of traceability and authenticity. The reduction in counterfeit products, enhancement of labor conditions, and elevated transparency have not only safeguarded the authenticity and quality of textile products but also fortified the reputation of the industry on a global scale. Bangladesh's textile sector stands as a powerful example of how blockchain can bolster traceability and authenticity in intricate supply chains, ensuring the industry's continued growth and integrity [30].

9. CONCLUSION

In conclusion, this paper has navigated the symbiotic relationship between blockchain technology and supply chain management, shedding light on its transformative influence on security, transparency, traceability, and authenticity. As evidenced by an in-depth exploration of literature and real-world case studies, blockchain technology has emerged not merely as a buzzword but as a tangible solution to age-old challenges in the supply chain domain. The decentralization and immutability inherent in blockchain architecture have redefined the operational landscape of supply chains. By securely recording data in an unalterable ledger, blockchain mitigates risks and instills a new level of accountability. The innovative applications and benefits outlined in this research paper underscore how blockchain catalyzes positive change in supply chain dynamics. The focal point of this paper has been the enhancement of traceability and the assurance of authenticity through blockchain adoption. The technology's ability to create transparent, unforgeable digital records facilitates end-to-end visibility into the movement of goods. Furthermore, by establishing a secure and tamper-proof digital trail, blockchain ensures the authenticity of products throughout their journey in the supply chain. The synthesis of findings strongly emphasizes the strides made in supply chain security and transparency, attributing these advancements to the widespread adoption of blockchain technology. The case studies presented showcase real-world applications, demonstrating the concrete impact of blockchain on operational efficiency and risk mitigation within supply chains. This research contributes significantly to understanding the transformative power of blockchain in supply chain management. The demonstrated potential of blockchain to shape the future of global trade is not merely theoretical but is supported by tangible evidence of its positive impact on key aspects of the supply chain. As the authors conclude, it is evident that blockchain technology is not merely a tool; it is a paradigm shift. Its integration into supply chain management marks a turning point, heralding a future where security, transparency, and accountability are not just ideals but intrinsic components of every supply chain operation. The journey has just begun, and as blockchain continues to evolve, its role in shaping the future of global trade will undoubtedly become increasingly profound.

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