



Energy-Efficient Blockchain Framework for Sustainable Green Supply Chain Integrity

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Abstract: For businesses attempting to achieve a sustainable balance between productivity and environmental sustainability, green supply chain management (GSCM) is a crucial component. Ensuring supply chains remain transparent, trackable and trustworthy, poses a challenge when you consider the globalized and complex nature of supply chain systems. Blockchain technology (a decentralized, immutable method of storing and managing data) is emerging as a potential solution to assist in some of these issues.

As a result, the majority of traditional proof of work blockchains exhibit significant levels of energy usage, thus making them ill-suited for use in sustainable environments. To address this issue, the current research presents a novel energy efficient blockchain framework that can aid with enhancing integrity along the green supply chain. To achieve this, the new framework uses a permissioned blockchain architecture incorporating multiple consensus algorithms (e.g., proof of stake, delegated proof of stake, byzantine fault tolerance and directed acyclic graph-based validation) that require a low amount of energy to validate transactions. The framework has been evaluated via a quantitative energy use analysis and an illustrative example of an environmentally sustainable food supply chain. Data supports that energy-efficient consensus methods can reduce blockchain energy use by greater than 90%, while also providing levels of: security, transparency and traceability consistent with those provided by proof-of-work systems. Results confirm that energy-efficient blockchain architectures create greater opportunities for widespread use of blockchain technology in green supply chain environmental systems and provide scalable and applicable approaches to sustainable supply chain management.

Keywords: Supply chain integrity, green supply chain, sustainability, consensus methods, and energy-efficient blockchain.

1. Introduction

Global supply chains are experiencing a significant transformation driven by concerns about climate change, stricter environmental regulations, and increasing stakeholder expectations for sustainable business practices. As well as checking out costs, how well items can be delivered, organizations are now evaluated against their environmental responsibility when it comes to procurement, manufacturing, logistics and distribution, and end of life product management. Green supply chain management (GSCM) is now a major method of reducing carbon emission, eliminating waste and utilizing resources more efficiently without compromising competitiveness. [1].

Despite advancements in digital supply chain technologies, conventional supply chain information systems remain

largely centralized and fragmented. These systems suffer from limited interoperability, lack of transparency, vulnerability to data manipulation, and reliance on trusted intermediaries. Such limitations impede effective traceability, weaken sustainability audits, and diminish trust among supply chain stakeholders, particularly when environmental claims and certifications must be verified across organizational boundaries. These difficulties are particularly important in green supply chains, where stakeholder trust and regulatory compliance depend on precise and unchangeable environmental data. Due to its decentralized, immutable, and transparent ledger structure, blockchain technology has garnered increasing attention as an alternate solution to some of these current supply chain issues. By allowing tamper-proof data-sharing amongst multiple parties, while also providing real-time visibility,



blockchain can improve traceability, accountability and trust among supply-chain networks [2][3]. Examples of how blockchain can be applied within supply chains include monitoring food safety, verifying ethical sourcing, preventing counterfeit products, and tracking carbon footprints, all of which support green supply chain management (GSCM) objectives [4]. Nevertheless, the adoption of blockchain in green supply chains has been limited by the high amount of energy consumed by many conventional blockchains that utilize Proof-of-Work (PoW) as their consensus mechanism.

Mining procedures that require heavy uses of computation to generate 'proof of work' (PoW) introduce significant energy usage associated with electricity, leading to large quantities of carbon emissions. The existence of significant environmental impact due to carbon emissions represents an inherent conflict between the use of blockchain technologies and the goal of sustainability [5]. Consequently, PoW-based blockchains are increasingly seen as unsuitable for environmentally conscious supply chain applications. Researchers and practitioners are looking into more energy-efficient blockchain consensus techniques, like Proof-of-Stake (PoS), Delegated Proof-of-Stake (DPoS), Byzantine Fault Tolerance (BFT), and Directed Acyclic Graph (DAG)-based architectures, to address this problem. These substitutes guarantee system security, scalability, and data integrity while drastically reducing computational requirements [6]. However, existing research often concentrates on individual mechanisms or theoretical discussions, with limited integration of system architecture, quantitative energy assessment, and application-specific validation for sustainable supply chains. This paper fills a gap in the current knowledge by proposing and evaluating an energy efficient blockchain platform for enhancing the integrity and sustainability of green supply chains. The primary contributions of this study are:

1. The creation of a permissioned, energy-efficient blockchain framework tailored for green supply chains;
2. Providing a quantitative comparison of different blockchain consensus mechanisms based upon energy consumption; and
3. A numerical case study for a green food supply chain to validate the practical viability of the proposed framework. This research demonstrates how energy-efficient blockchain architectures can result in an energy savings of more than 90% compared with traditional proof-of-work (PoW) systems, while maintaining transparency and security. The results from this study provide practical data on ways to implement sustainable blockchain solutions within real-world green supply chains.

2. Literature Review

2.1 Blockchain Technology in Supply Chain Management

Blockchain provides a system to record transactions, securely and in a decentralized way, without an intermediary. In the supply chain industry, blockchain creates more transparency, traceability, and trust among stakeholders by permanently recording and providing verification of transactions [2]. These benefits may solve long-standing problems related to data fragmentation, limited visibility, and distrust of multi-actor supply chain networks. Connecting blockchain with Internet of Things (IoT) technologies adds even greater strength to the supply chain operation through real-time data capture, sharing of data automatically, and more accurate data [3]. Prior studies demonstrate successful blockchain applications in agri-food and manufacturing supply chains, particularly for food safety monitoring, ethical sourcing verification, and counterfeit prevention [4]. These applications support accountability and end-to-end visibility, which are essential for sustainability-oriented supply chains.

2.2 Green Supply Chain Management

Green supply chain management (GSCM) is concerned with including environmental issues throughout the supply chain, including sustainable sourcing, energy efficient manufacturing, environmentally friendly transport and responsible waste disposal. The goal of organizations using GSCM is to decrease carbon emissions and their negative impact on the environment, while increasing resource productivity and maintaining economic profitability and competitive advantage [1]. The use of digital technology to provide accurate, transparent and up-to-date environmental information is vital for enabling GSCM processes, however there are still barriers to technology adoption such as the ability to integrate new technologies into the existing environment and organizational readiness to implement those technologies successfully [7]. Blockchain supports GSCM by facilitating transparent sustainability reporting, verifiable environmental claims, and improved regulatory compliance across supply chain partners [8][9].

2.3 Energy Consumption Challenges of Blockchain Systems

Although it has a lot of potential, there are a number of concerns regarding the functionality of the blockchain technology, especially with respect to Proof-of-Work (PoW), particularly regarding energy usage and consumption. Since PoW focuses on computational operations to validate transactions, the consumption of electricity and generation of greenhouse gas emissions in a PoW blockchain may exceed the total consumption and



generation of emissions in many small to medium-sized countries (such as The Bahamas and Puerto Rico) [5]. Therefore, many researchers are focusing on developing alternative consensus mechanisms that meet the robustness and security standards set forth with PoW, while also minimizing overall energy consumption for a more sustainable solution.

2.4 Energy-Efficient Consensus Mechanisms and Research Gap

BFT, PoS, DPoS, and DAG-based consensus mechanisms all provide a way to reach consensus with minimal processing power and resources while still allowing for security, scalability and energy efficiency within the system [5][6]. These types of consensus mechanisms are particularly effective for enterprise or permissioned blockchain systems. The majority of implementations either rely on energy-intensive PoW or lack a comprehensive framework integrating sustainability, architecture, and performance evaluation, despite the fact that previous research demonstrate their promise [10]. In order to close this gap, this study proposes and validates an energy-efficient blockchain infrastructure designed especially for the integrity of green supply chains.

3. Research Methodology

In order to assess the viability of implementing energy-efficient blockchain technology in green supply chain management, this study uses a design-oriented research methodology that combines system framework construction, quantitative energy-consumption analysis, and a numerical case study. In order to ensure both theoretical rigor and practical applicability, the process is organized to move methodically from problem identification to solution creation and empirical evaluation.

3.1 Research Design

The study employs a design science methodology, which is appropriate for tackling intricate engineering and information system problems where the goal is to create and assess an artifact. An energy-efficient blockchain system designed for green supply chain integrity serves as the study's artifact. The framework's architecture is influenced by supply chain operations, sustainability needs, and blockchain system limitations. Existing research is leveraged carefully to define system assumptions, set benchmark energy-consumption metrics, and assist design decisions rather of performing a stand-alone review study. Instead than summarizing earlier research, the framework design and quantitative assessment are the research's main contributions.

3.2 Methodological Phases

There are four primary stages to the methodology:

1. **Requirement analysis and problem identification:** Conventional Proof-of-Work (PoW)-based blockchain systems are shown to have energy inefficiencies, especially in supply chain applications that prioritize sustainability. Green supply chain goals are used to establish both functional and non-functional needs, such as traceability, transparency, security, scalability, and energy efficiency.
2. **Architecture Development and Framework Design:** A permissioned blockchain architecture is used to create an energy-efficient blockchain framework. To do away with energy-intensive mining, low-energy consensus techniques such as Proof-of-Stake (PoS), Delegated Proof-of-Stake (DPoS), Byzantine Fault Tolerance (BFT), and Directed Acyclic Graph (DAG)-based validation are used. Automated data collection, smart contract validation, and unchangeable recordkeeping are supported by the conceptual architecture and transaction process.
3. **Quantitative Energy-Consumption Analysis:** Normalized energy-consumption measures are used to compare blockchain consensus methods. To measure the possible decrease attained by energy-efficient processes in comparison to PoW-based systems, energy use is assessed in relation to transaction validation and throughput.
4. **Case Study Validation:** A numerical case study that depicts a green food supply chain is used to validate the suggested framework. The case study evaluates practical viability and energy efficiency by simulating actual operating settings.

3.3 Setting Up and Assessing Case Studies

A hypothetical green food supply chain with 25 linked nodes—producers, processors, shipping companies, retailers, and regulatory bodies—is examined in this case study. Every day, the system handles about 10,000 transactions that include retail distribution, certification verification, transportation updates, environmental monitoring, and manufacturing records. Extrapolating per-transaction energy use for various consensus processes under the same conditions yields an estimate of annual energy consumption.

Energy efficiency, scalability, security and integrity, traceability, and sustainability alignment are the criteria used to evaluate the framework. All assumptions are based

on well-established blockchain models to guarantee methodological validity, and normalized energy measures are employed to facilitate uniform comparison among consensus processes.

4. Suggested Blockchain Framework for Energy Efficiency

The suggested energy-efficient blockchain framework for improving sustainability, integrity, and transparency in green supply chain management is presented in this section. By incorporating low-energy consensus techniques while maintaining essential blockchain characteristics like security, immutability, and traceability, the framework overcomes the drawbacks of traditional Proof-of-Work (PoW)-based blockchain systems. It is especially designed for multi-stakeholder supply chain settings where data dependability, environmental performance, and regulatory compliance are crucial.

4.1 Framework Design Goals

Five main design goals serve as the framework's compass. By removing computationally demanding mining procedures connected to PoW, energy efficiency is given first priority. Immutable transaction records and shared data visibility among stakeholders guarantee supply chain integrity. Large supply chains typically have significant transaction volumes, which are supported by scalability. Smart contracts are used to automate the enforcement of operational logic and sustainability regulations. Lastly, auditable and verifiable access to supply chain data facilitates regulatory compliance. When combined, these goals guarantee that the criteria of green supply chain management (GSCM) and blockchain system architecture are in harmony.

4.2 Conceptual Design

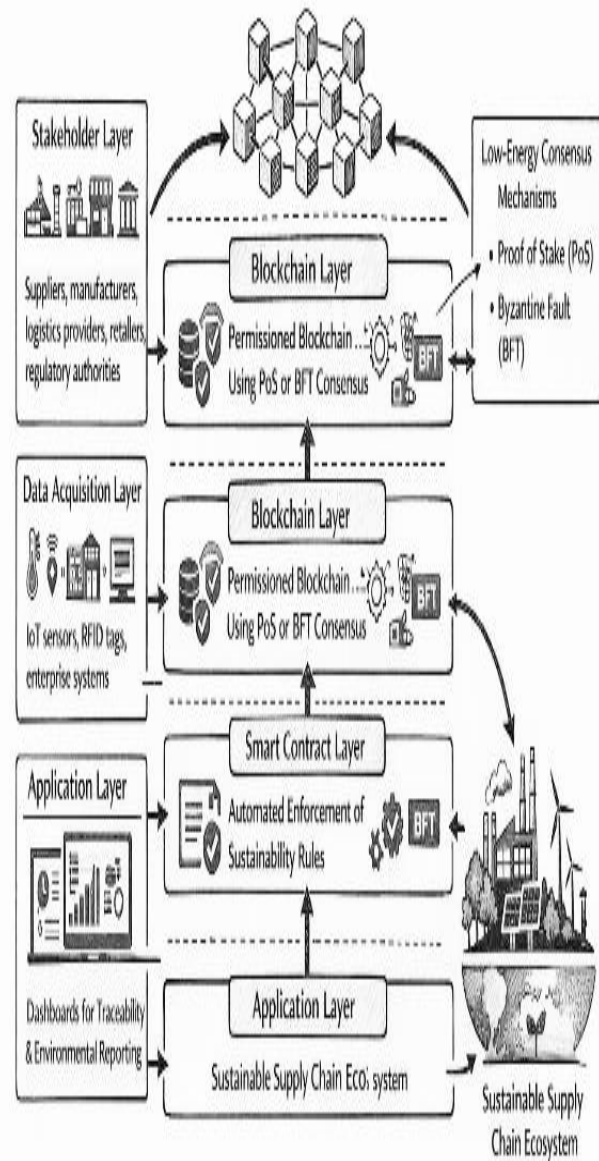


Figure 1: The suggested framework's conceptual design

Five closely connected layers make up the multi-layered architecture seen in Figure 1. In order to maintain responsibility and secrecy, the stakeholder layer comprises manufacturers, suppliers, retailers, logistics companies, and regulatory bodies. Each of these entities operates a node or has restricted access depending on predetermined rights. The data gathering layer gathers real-time operational and environmental data, including temperature, energy consumption, transportation status, and emissions, by integrating IoT sensors, RFID tags, and business systems.

Accuracy and dependability are increased via automated data collection.

Fundamentally, the blockchain layer uses a permissioned network with energy-efficient consensus techniques like Byzantine Fault Tolerance (BFT) and Proof-of-Stake (PoS). Eliminating mining-based validation guarantees tamper-resistant and immutable data storage while drastically lowering energy usage. Transaction validation, certification verification, sustainability compliance checks, and payment execution are all automated by the smart contract layer. Lastly, the application layer enables transparency for customers and regulators by offering dashboards and interfaces for traceability, sustainability reporting, compliance audits, and performance monitoring.

4.3 Security, Energy Efficiency, and Transaction Validation

Validation

Every supply chain event is documented as a blockchain transaction after smart contract validation and energy-efficient consensus, as shown in Figure 2. Consensus optimization, permissioned validator selection, and parallel processing motivated by DAG-based validation are used to promote energy efficiency. The system uses digital signatures, cryptographic hashing, and access control techniques to provide high security while putting efficiency first. All things considered, the suggested architecture provides a scalable, safe, and long-lasting basis for digital transformation in green supply chains.

5. Transaction Validation and Traceability Workflow

This section outlines the transaction validation and traceability workflow of the proposed energy-efficient blockchain framework for managing green supply chains. The workflow guarantees secure data capture, automated validation, and unchangeable recordkeeping throughout all supply chain phases while reducing energy use.

5.1 Workflow Overview

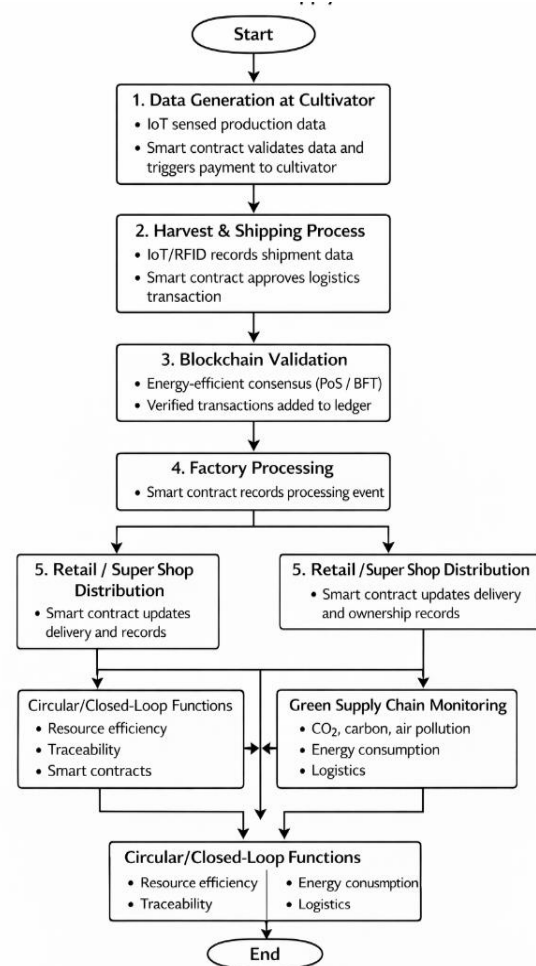


Figure 2: Transaction Validation and Traceability Workflow in a Blockchain

By utilizing a permissioned blockchain network to record, validate and verify supply chain transactions, the transaction workflow is designed to be a decoupled approach (i.e., an approach with no dependency between subcomponents) to sequencing events of the supply chain. Each transaction has a corresponding supply chain activity in the real world, such as raw material sourcing, production, transportation, processing, and retail distribution. Additionally, this workflow is designed for real-time traceability, preventing manipulation of data and providing the ability to conduct sustainability audits transparently.

5.2 Data Generation and Collection

At every supply chain stage, operational and environmental data are generated via IoT sensors, RFID tags, and enterprise information systems. This data includes product identifiers, timestamps, location details, temperature and humidity conditions, energy consumption, and

sustainability certifications. Automated data collection minimizes manual intervention and improves data accuracy.

5.3 Smart Contract-Based Validation

Before a transaction is added to the blockchain, the collected data is assessed by smart contracts. These smart contracts encode predefined business rules and sustainability criteria, such as acceptable temperature ranges for perishable goods, compliance with environmental standards, or verification of certification documents. Transactions meeting all conditions are approved for submission, while those that do not comply are rejected or flagged for further review.

5.4 Energy-Efficient Consensus and Block Formation

Once validated, the transactions are sent to the blockchain layer; the consensus is reached through energy-efficient methods such as PoS, DPoS or BFT. In contrast to PoW, which requires significant quantities of electricity to mine, these consensus methods use a dramatically reduced amount of electricity. Once consensus has been determined, each block will hold transactions, or if using a DAG-based architecture, the transactions will each be validated independently in parallel.

5.5 Immutable Storage and Distributed Ledger Update

After validation, transactions are cryptographically hashed and permanently recorded in the distributed ledger. Each block is connected to previous records, ensuring immutability and resistance to tampering. All authorized nodes in the network maintain synchronized copies of the ledger, ensuring data consistency and fault tolerance.

5.6 End-to-End Traceability and Auditability

The immutable nature of the blockchain allows for end-to-end traceability across the entire supply chain lifecycle. Stakeholders can trace products from origin to final delivery, while regulators and auditors can access historical transaction records for compliance verification. Consumers can also verify product provenance and sustainability attributes through application-layer interfaces.

5.7 Workflow Efficiency and Sustainability

Impact By integrating automated data capture, smart contract validation, and low-energy consensus mechanisms, the proposed workflow reduces processing delays and energy consumption while maintaining security and transparency. This approach ensures that blockchain-enabled traceability systems support, rather than hinder, the environmental goals of green supply chain management.

6. Consensus Mechanism Adoption Analysis

This section examines how blockchain consensus mechanisms are being adopted in supply chain and

sustainability-focused applications, with a special emphasis on their appropriateness for green supply chain management. The analysis offers empirical support for choosing energy-efficient consensus mechanisms in the proposed blockchain framework.

6.1 Adoption Trends of Blockchain Consensus Mechanisms

Blockchain consensus mechanisms are crucial in shaping system performance, security, scalability, and energy usage. Initially, blockchain implementations mainly used Proof-of-Work (PoW) because of its robust security and decentralization features. However, the significant computational and energy requirements of PoW have raised serious concerns about its environmental sustainability, especially in applications aimed at green supply chain goals. As sustainability has become more important, researchers and practitioners have increasingly investigated alternative consensus mechanisms that lower energy consumption while maintaining adequate security and performance. These alternatives include Proof-of-Stake (PoS), Delegated Proof-of-Stake (DPoS), Byzantine Fault Tolerance (BFT)-based mechanisms, and hybrid or permissioned consensus models.

6.2 Analysis of Adoption Distribution

Consensus Mechanism	Number of Studies	Adoption Share (%)
Proof-of-Work (PoW)	17	27
Practical Byzantine Fault Tolerance (PBFT)	13	21
Delegated Proof-of-Stake (DPoS)	6	10
Proof-of-Stake (PoS)	5	8
Proof-of-Authority (PoA)	4	6
Proof-of-Reputation (PoR)	3	5
Other / Hybrid Mechanisms	11	23

Table 1 outlines the distribution of consensus mechanisms reported in previous blockchain-based supply chain applications

The findings show that PoW is still present in a significant number of studies; however, there is a noticeable shift towards energy-efficient mechanisms. BFT-based consensus mechanisms are widely adopted in enterprise and permissioned blockchain settings due to their low latency and reduced energy needs. PoS and DPoS are increasingly used for applications that require scalability and

sustainability, while Proof-of-Authority (PoA) and Proof-of-Reputation (PoR) are found in controlled and trust-based network environments. The presence of hybrid and alternative mechanisms further indicates ongoing experimentation to balance energy efficiency, decentralization, and security. This variety highlights the lack of a universal solution and emphasizes the importance of selecting consensus mechanisms based on specific application needs.

6.3 Implications for Green Supply Chain Applications

From a green supply chain perspective, the adoption trends show a growing awareness that energy efficiency is a crucial design criterion for blockchain systems. PoW-based consensus mechanisms are increasingly seen as incompatible with sustainability goals due to their high electricity consumption and related carbon emissions. In contrast, PoS-, DPoS-, and BFT-based mechanisms provide a more favorable balance between energy efficiency, performance, and security. These findings support the design choice of the proposed energy-efficient blockchain framework, which prioritizes low-energy consensus mechanisms within a permissioned network. By aligning consensus selection with environmental and operational needs, the framework ensures that blockchain adoption enhances supply chain sustainability rather than undermining it.

6.4 Summary of Findings

The analysis of the current consensus mechanisms confirms that both blockchain research and practice are moving away from energy-intensive Proof-Of-Work (PoW) systems to more sustainable consensus alternatives. This growing shift away from energy-intensive PoW systems provides an excellent empirical foundation which supports the overall objective of creating a framework to potentially deploy blockchain technology in green supply chain environments without negatively affecting environmental objectives.

7. Results and Discussion

In the next sections, I will give you an overview of the results obtained from quantitative analysis on energy consumption, along with the case study numerically used to assess the energy-efficient Blockchain Framework that was developed for green supply chain management. From these results we can see evidence that utilizing low energy Consensus algorithms will significantly decrease the environmental footprint of a blockchain system while providing an adequate level of security, transparency, and traceability.

7.1 Relative Energy Consumption of Blockchain Consensus Mechanisms

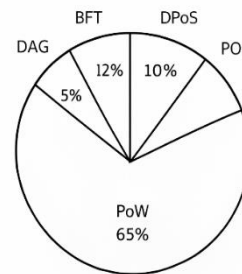


Figure 3 : Relative Energy Consumption Share of Blockchain Consensus Mechanisms

Normalized values are used to display a overall view of the distribution of the most popular consensus mechanism types. The largest percentage of total energy will be for Proof of Work (PoW) which makes up approximately 65% of total energy usage across blockchains. The majority of energy used for PoW is due to continuous computing power consumption required for proof-of-work operations while validating blocks between peers. The remaining types of consensus mechanisms are energy efficient since they require significantly less total energy consumption than PoW (see below): PoS - approximately 8% of total energy consumption; DPoS - approximately 10%; BFT - approximately 12%. Directed Acyclic Graph (DAG)-based architectures have the lowest energy consumption at 5%, reflecting their ability to validate transactions in parallel without relying on block mining. These results confirm that replacing PoW with energy-efficient consensus mechanisms can significantly reduce the energy footprint of blockchain systems and directly support the design choices made in the proposed framework.

7.2 Case Study Results: Green Food Supply Chain

To evaluate practical feasibility, a numerical case study of a green food supply chain was conducted. The modeled supply chain included 25 interconnected nodes, such as producers, processors, logistics providers, retailers, and regulatory authorities, handling about 10,000 transactions daily. These transactions included production records, environmental monitoring data, transportation updates, certification verification, and retail distribution activities. Under a PoW-based blockchain system, the estimated annual energy consumption exceeded 160,000 kWh, mainly due to energy-intensive mining operations. Such energy use undermines the environmental goals of green supply chain management and raises operational costs. When the same scenario was assessed using a PoS-based consensus mechanism, annual energy consumption dropped to about 9,000 kWh, representing a 94.4% reduction in energy use.



BFT-based implementations showed similar energy efficiency, with slightly higher communication overhead but improved transaction throughput and lower latency.

7.3 Performance and Sustainability Implications

Beyond energy efficiency, low-energy consensus mechanisms offer significant performance benefits. PoS and BFT-based systems provide higher transaction throughput and lower confirmation latency than PoW-based systems, making them ideal for real-time supply chain applications. The permissioned network design further enhances scalability by limiting validator participation while maintaining security and fault tolerance. From a sustainability standpoint, the significant reduction in energy consumption directly translates into lower carbon emissions, reduced operational costs, and better alignment with environmental regulations. The integration of blockchain with IoT-based data acquisition and smart contract automation further enhances transparency, traceability, and continuous environmental monitoring.

7.4 Summary of Key Insights

The overall conclusion of the study is that PoW-based blockchain systems are not viable for green supply chain applications because of their very large energy consumption. Examples of energy-efficient consensus mechanisms reduce energy usage by more than 90% and permissioned blockchain architectures permit scaling up and improving performance and sustainability. Therefore, the conclusions from this research suggest that the proposed framework provides a viable and sustainable means of improving both the integrity and transparency of green supply chain management.

8. Extended Discussion: Sustainability Impact

This section explores the wider sustainability effects of implementing the proposed energy-efficient blockchain framework within green supply chain management. Beyond enhancing technical performance and reducing energy use, the framework supports the environmental, economic, and social aspects of sustainability, which are crucial for sustainable supply chain practices and long-term value creation.

8.1 Environmental Sustainability Impact

The most significant sustainability impact of the framework is the reduction of energy consumption and associated carbon emissions. This is achieved by replacing Proof-of-Work (PoW) with low-energy consensus mechanisms such as Proof-of-Stake (PoS) mechanism, Byzantine Fault Tolerance (BFT) consensus, and a Directed Acyclic Graph (DAG) validation methodology, resulting in a decrease in

energy usage when validating transactions. Several case study analyses have shown that there is a greater than 90% reduction in energy consumption. This translates into less greenhouse gas emissions emitted when large-scale blockchain networks are deployed. In addition, IoT-enabled data acquisition supports the continuous tracking of environmental atmospheric conditions (i.e., temperature, humidity) and overall energy consumption along the supply chain. This real-time insight aids in the early detection of inefficiencies, reduces spoilage and waste—especially in perishable goods supply chains—and enhances overall environmental performance. As a result, the framework supports both emission reduction and resource efficiency goals, aligning blockchain adoption with circular economy principles while addressing potential sustainability trade-offs [11].

8.2 Economic Sustainability Impact

From an economic standpoint, the adoption of energy-efficient blockchain technologies lowers operational costs related to electricity consumption, specialized hardware, and system maintenance. By eliminating energy-intensive mining infrastructure, entry barriers are reduced, making blockchain deployment more financially feasible for small and medium-sized enterprises involved in green supply chains. Furthermore, improved transparency and traceability decrease costs associated with fraud, disputes, and manual auditing. Automated smart contracts streamline compliance verification, certification validation, and payment execution, enhancing operational efficiency and reducing administrative overhead. These advantages improve supply chain coordination and bolster the long-term financial sustainability of supply chain ecosystems.

8.3 Social Sustainability and Regulatory Implications

Social sustainability is bolstered through increased transparency, accountability, and trust among supply chain stakeholders. The immutable and shared ledger ensures that sustainability claims, certifications, and environmental data are verifiable and resistant to manipulation, thereby reducing the risk of greenwashing and strengthening consumer confidence in environmentally responsible products. The framework also aids regulatory compliance by allowing authorities and third-party auditors to access reliable historical records for verification purposes. Blockchain-enabled traceability simplifies adherence to environmental regulations and sustainability reporting standards by providing accurate, auditable, and real-time data. On a broader scale, incorporating energy efficiency into blockchain system design illustrates how digital transformation and sustainability objectives can be aligned rather than conflicting.

8.4 Summary of Sustainability Impact

In summary, the extended analysis confirms that the proposed framework positively impacts all three pillars of sustainability: environmental (reduced energy consumption and emissions), economic (lower operational costs and improved efficiency), and social (enhanced transparency, trust, and regulatory compliance). These impacts reinforce the role of energy-efficient blockchain technologies as foundational enablers of sustainable and resilient green supply chains.

9. Challenges and Future Research Directions

This blockchain framework for minimizing energy consumption could improve sustainability, transparency, and integrity of green supply chains; however, there are still many hurdles that exist before this can be implemented on a larger scale in real-world applications. This section identifies the main challenges; Technical Issues, Non-Technical Issues and Operational Issues. Additionally, potential areas of further study are explored.

9.1 Integration with Legacy Systems

Adopting blockchain technology will be a major difficulty for businesses because current supply chain management systems are still using outdated technologies to connect to the rest of the supply chain. Companies have established their supply chains using traditional (centralized/nondistributed) methods in the form of enterprise resource planning (ERP) systems, warehousing, and logistics software packages, all of which require a central repository of information. Thus, any company currently using one of these traditional supply chains faces major obstacles to adopting blockchain technology because their supply chains are tied to their legacy systems. Therefore, the development of an interoperable connection between blockchain and a legacy system will involve developing and providing standard data models, middleware solutions, and application programming interface (API) solutions, in order to create a seamless data transfer process. To this end, future research should support the creation of scalable framework solutions for integration as well as the establishment of inter-operational standards so that data can be transferred seamlessly while preserving the operational effectiveness of the supply chain.

9.2 Governance and Network Management

Effective governance is a significant challenge, especially in permissioned blockchain environments involving multiple independent stakeholders. Issues related to node participation, validator selection, access control, and decision-making authority can impact trust, accountability, and system performance. Although energy-efficient

consensus mechanisms reduce computational overhead, they introduce governance complexity in defining roles and responsibilities among participants. Future studies should explore governance models that balance decentralization, accountability, and efficiency, including consortium-based and hybrid governance structures tailored to supply chain ecosystems.

9.3 Data Privacy and Confidentiality

While blockchain enhances transparency, excessive data visibility may conflict with privacy and confidentiality requirements in competitive supply chain environments. Sensitive commercial information, such as pricing strategies, supplier relationships, and proprietary operational data, must be adequately protected. Techniques such as encryption, off-chain storage, zero-knowledge proofs, and role-based access control can mitigate these concerns. Future research should investigate privacy-preserving blockchain architectures that maintain traceability and auditability while safeguarding sensitive information.

9.4 Scalability and Performance Trade-offs

Although energy-efficient consensus mechanisms significantly improve scalability compared to Proof-of-Work, performance trade-offs may still arise as transaction volumes and network size increase. Communication overhead in Byzantine Fault Tolerance (BFT)-based systems and coordination complexity among large validator sets can limit scalability. Future research should focus on optimizing consensus protocols, exploring sharding and layer-two solutions, and evaluating adaptive or hybrid architectures that dynamically adjust to workload variations.

9.5 Standardization and Energy Optimization

A major limitation in current blockchain-enabled green supply chain applications is the lack of standardized sustainability metrics for measuring environmental performance. Differences in carbon accounting methods, energy measurement approaches, and sustainability indicators hinder cross-organizational comparison. Additionally, real-time monitoring of blockchain energy consumption remains limited. Future work should aim to develop standardized sustainability metrics and integrate real-time energy monitoring tools that enable adaptive optimization of blockchain operations.

9.6 Research Outlook

Addressing these challenges is essential for advancing the adoption of energy-efficient blockchain technologies in green supply chains. Future research combining technical innovation, governance design, standardization efforts, and large-scale industrial experimentation will be critical for realizing the full sustainability potential of blockchain-enabled supply chain systems.

10. Conclusion

This study proposed and evaluated an energy-efficient blockchain framework for improving sustainability, transparency, and integrity in green supply chain management. The research developed a permissioned blockchain architecture and integrated several low-energy consensus mechanisms (i.e., Proof of Stake [PoS], Delegated Proof of Stake [DPoS], Byzantine Fault Tolerance [BFT], and Direct Acyclic Graph [DAG]-based validations) to solve the incompatibility between the sustainability objective and energy-intensive Proof of Work (PoW) blockchain systems. The suggested framework showed energy savings of more than 90% as compared to PoW-based systems through quantitative energy-consumption analysis and a numerical case study of a green food supply chain. These results demonstrate that energy-efficient consensus algorithms improve transaction throughput, latency, and scalability while also greatly reducing environmental impact, making blockchain appropriate for supply chain applications that prioritize sustainability and real-time. Beyond energy savings, the framework improves supply chain integrity through end-to-end traceability enabled by IoT-based data capture, automated compliance enforcement using smart contracts, and unchangeable recordkeeping. These features improve regulatory compliance, boost stakeholder confidence, and lower the dangers of data tampering and greenwashing. Overall, this study shows that sustainability goals and blockchain technology are not intrinsically at odds. Blockchain can be a fundamental enabler of transparent, resilient, and environmentally conscious supply chains when it is designed with energy efficiency and application-specific requirements in mind. This provides a workable pathway for sustainable digital transformation across global supply chain ecosystems.

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