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Blockchain Application in Food Supply Chains: A Critical Review and Agenda for Future Studies

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Abstract: Blockchain technology (BCT) has emerged as a transformative tool in food supply chain management (FSCM), offering enhanced transparency, traceability, and trust. This paper critically reviews the application of blockchain in FSCM, synthesizing findings from theoretical and empirical studies to assess its effectiveness in addressing food safety, fraud prevention, and regulatory compliance. The review highlights blockchain's potential to improve transparency and traceability through immutable, decentralized ledgers, enabling real-time tracking of products from farmers to consumers. Case studies, such as IBM Food Trust's collaboration with Walmart, demonstrate significant reductions in traceability time and improved consumer trust. Additionally, blockchain's integration with IoT and big data analytics enhances food safety by enabling real-time monitoring of environmental conditions and automating recall processes, thereby reducing public health risks and economic losses.

Despite its potential, the adoption of blockchain in FSCM faces several challenges, including technical complexity, scalability issues, regulatory ambiguities, and the need for industry-wide collaboration. The review identifies gaps in the current literature, such as the lack of comprehensive, empirically validated frameworks and longitudinal studies assessing the long-term impacts of blockchain integration. Furthermore, the paper discusses blockchain's economic and sustainability implications, emphasizing its role in reducing administrative costs, minimizing fraud, and optimizing inventory management.

The review concludes with a future research agenda, recommending empirical validation of blockchain's impact, developing hybrid systems integrating blockchain with AI and IoT, and establishing standardized regulatory frameworks. Collaborative efforts among industry stakeholders, governments, and technology providers are essential to overcoming adoption barriers and ensuring equitable benefits across the supply chain. This paper underscores the necessity for interdisciplinary research and cross-sector collaboration to realize blockchain's transformative potential in FSCM, ultimately enhancing food safety, quality control, and sustainability.

Keywords: *Blockchain, Food Supply Chain, Traceability, Transparency, Regulatory Compliance, IoT, AI, Sustainability.*

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I. INTRODUCTION

Blockchain technology (BCT) was first conceptualized by Nakamoto (2008) as the underlying framework for Bitcoin. It has evolved into a transformative innovation with applications extending far beyond cryptocurrency. Characterized by a decentralized, distributed ledger system, blockchain provides secure peer-to-peer transactions without intermediary systems (Nakamoto, 2008). The decentralized and distributed ledger system features of blockchain eliminate the need for central intermediaries and provide robust mechanisms for secure, peer-to-peer transactions (Nakamoto, 2008; Tapscott & Tapscott, 2016). FSCM is a multidimensional network involving farmers, processors, distributors, retailers, and consumers. Blockchain technology offers a promising solution to longstanding challenges such as data opacity and inefficiencies in traceability (Chang et al., 2019). By integrating blockchain with complementary technologies like big data analytics and the Internet of Things (IoT), scholars and practitioners envision a future where food safety, quality control, and regulatory adherence are significantly enhanced (Tian, 2016; Kamath, 2018).

II. THEORETICAL BACKGROUND AND LITERATURE REVIEW

- *Fundamental Blockchain Principles*

Blockchain is characterized by decentralization, immutability, and transparency. Proof of Work (PoW) and Proof of Stake (PoS) consensus mechanisms underpin its secure operation, though debates continue over energy efficiency and scalability (Eyal & Sirer, 2013; Buterin, 2021). The advent of smart contracts on platforms like Ethereum has expanded blockchain's applicability to domains requiring automated and tamper-proof record-keeping (Buterin, 2015). Blockchain's immutability means that once data is recorded, it cannot be changed retroactively. Narayanan et al. (2016) attribute this to cryptographic hashing and consensus protocols, which make tampering economically and computationally infeasible. This feature is particularly valuable in sectors like supply chain management and finance, where auditability is critical (Tapscott & Tapscott, 2016). Blockchain's first application was Bitcoin, a decentralized currency that challenged traditional financial systems (Nakamoto, 2008). Zyskind and Nathan (2015) further demonstrated blockchain's potential in decentralized identity management, enabling users to control personal data without third-party intermediaries.

- *Blockchain in FSCM*

The food supply chain is a diverse network involving numerous stakeholders and complex processes. The stakeholders include farmers, processors, distributors, retailers, and consumers. Ensuring transparency, traceability, and efficiency in this network is crucial for maintaining food safety, reducing waste, and enhancing consumer trust. Traditional supply chain management systems often fail to address these challenges due to inherent limitations, such as lack of transparency, inefficiencies in data sharing, and vulnerability to fraud (Chang et al., 2019).

BCT is considered a transformative tool in the food supply chain industry because of its capacity to address inefficiencies related to transparency, traceability, and coordination (Kamath, 2018). BCT improves FSCM by providing a secure and transparent platform for recording and sharing transaction data among supply chain participants (Christidis & Devetsikiotis, 2016). Proponents argue that blockchain can enhance traceability, reduce fraud, and improve food safety by enabling real-time tracking of products (Paliwal et al., 2020). Blockchain promotes supply chain transparency by providing real-time tracking of goods. In the context of FSCM, blockchain's immutable ledger ensures real-time tracking of food products from farm to fork.

Case studies such as IBM Food Trust's collaboration with Walmart, which reduced traceability time dramatically, illustrate how blockchain can minimize fraud, streamline recalls, and improve consumer trust (IBM, 2020; Pilkington, 2016). Further, integrating blockchain with IoT sensors provides granular monitoring of critical parameters (e.g., temperature and humidity), ensuring compliance with food safety standards (Tian, 2016; Feng et al., 2020). While numerous studies have demonstrated blockchain's potential to improve supply chain transparency and traceability, recent reviews also highlight gaps in empirical validation and the challenges of large-scale implementation (Saberi et al., 2018; Casino et al., 2019). Issues such as technical complexity, interoperability with legacy systems, and the need for industry-wide collaboration remain significant barriers (Kshetri, 2018; Kouhizadeh et al., 2021).

III. RESEARCH GAP

Although the literature on blockchain in FSCM has expanded in recent years, several gaps remain. First, many studies focus on conceptual models or isolated case studies rather than comprehensive, empirically validated frameworks. Second, the practical barriers to implementation, including technical challenges, interoperability challenges, scalability limitations, regulatory ambiguities that complicate cross-border adoption, and stakeholder resistance, are often discussed superficially. Finally, there is a paucity of longitudinal research assessing the long-term impacts of blockchain integration in FSCM, particularly concerning cost savings, operational efficiency, and public health outcomes and its differential impact on small- and medium-sized enterprises (SMEs) versus larger corporations. These gaps underscore the need for systematic empirical studies and standardized

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methodological approaches that bridge theoretical promise with real-world performance. Addressing these gaps is essential for developing actionable strategies that facilitate the widespread adoption of blockchain technologies.

IV. OBJECTIVES AND METHODS

➢ *Objectives*

This review's broad objective is to examine the existing literature on blockchain applications in FSCM critically. Specific aims include:

- Evaluate blockchain's impact on transparency, traceability, and food safety.
- Assess the economic and sustainability implications of using blockchain technology in FSC
- Identify technical, regulatory, and collaborative barriers to adoption.
- Propose a future research agenda integrating blockchain with complementary emerging technologies.

➢ *Methods*

The literature review was conducted systematically using major academic databases (e.g., Web of Science, Scopus, Google Scholar). Keywords such as "blockchain," "food supply chain," "traceability," "transparency," and "sustainability" were used to identify peer-reviewed articles published between 2015 and 2023. Inclusion criteria focused on studies addressing empirical applications, case studies, and conceptual frameworks. Search strings such as:

TITLE-ABS-KEY ("Blockchain integrated with supply chain" AND "Food Supply chain" AND ("Transparency" OR "Traceability" OR "Efficiency"))

were employed to capture a comprehensive spectrum of research. The quality of the selected studies was assessed using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, focusing on study design, data reliability, and transparency in reporting. Exclusion criteria were applied to eliminate studies with incomplete data, lack of statistical analysis, or non-comparative designs. Studies were then critically appraised for methodological rigor, relevance, and contribution to the field. This systematic approach ensured the inclusion of robust evidence.

V. RESULTS AND DISCUSSION

A. *Enhanced Transparency and Traceability*

Among the most evident advantages of blockchain technology in FSCM is its ability to improve transparency and traceability. By employing an immutable and decentralized ledger of transactions, blockchain provides supply chain actors with access to real-time data on the movement of products from production to consumption (Paliwal et al., 2020). This transparency can mitigate fraud and ensure compliance with regulatory standards, as any tampering with the data would be easily detectable.

Feng et al. (2020) expanded on this by combining blockchain with IoT and big data analytics, showing how real-time monitoring of storage conditions (e.g., temperature) enhances transparency. These studies highlight blockchain's potential to resolve longstanding issues like fraud and mislabeling, particularly in complex, globalized supply chains. Current data reveal that consumers increasingly demand transparency regarding food origins and safety; blockchain offers a robust solution to track products from source to destination and verify their authenticity (Kamilaris et al., 2019).

Traceability in food supply chains requires monitoring products across all stages, including production, processing, and distribution. Blockchain enables real-time tracking by recording each transaction as an immutable block, creating a transparent audit trail. For instance, Tian (2016) proposed an early blockchain framework for food traceability, demonstrating how decentralized record-keeping reduces data tampering risks. Tian (2016) further designed a blockchain-integrated system using RFID tags to trace agricultural products, significantly reducing data tampering risks. This system allows stakeholders to access real-time data on product location and handling conditions, ensuring compliance with safety standards. A prominent example is IBM's Food Trust platform, which leverages blockchain to streamline traceability. Walmart's collaboration with IBM reduced the time to trace mangoes from seven days to two seconds, demonstrating blockchain's efficiency in mitigating foodborne illness outbreaks (IBM, 2020). Such systems enhance recall accuracy, minimize waste, and build consumer trust (Feng et al., 2020).

Provenance verification ensures products' origins and authenticity, crucial for certifications like organic or geographical indications (GIs). Blockchain's immutability provides a reliable record of a product's journey. Similarly, Caro et al. (2018) developed a Hyperledger Fabric-based prototype, AgriBlockIoT, which integrates IoT sensors to automate data logging, improving accuracy in perishable goods tracking. Caro et al. (2018) further implemented the Hyperledger Fabric to track organic olive oil, verifying that non-organic inputs were excluded at every stage. This application prevents fraud, such as false labeling of GIs like Champagne or Parmigiano-Reggiano, by cryptographically sealing data from certified farms (Kshetri, 2018). Blockchain also combats unethical practices in seafood supply chains. The World Wildlife Fund's Blockchain Supply Chain Traceability Project documented how tuna catches in Fiji were recorded on a blockchain, ensuring legal sourcing and reducing illegal fishing (Kamilaris et al., 2019).

Blockchain's decentralized ledger provides an immutable record of every transaction, thereby significantly enhancing supply chain transparency. Empirical evidence from initiatives like IBM Food Trust demonstrates that blockchain can reduce traceability times from days to seconds, enabling rapid responses during contamination outbreaks (IBM, 2020; Kamath, 2018). Such transparency empowers consumers to make ethical purchasing decisions.

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B. Improvement in Food Safety and Quality Control

Blockchain provides real-time data access in the food supply chain, significantly impacting food safety. Chen et al. (2021) illustrated its role in rapidly automating recalls by pinpointing contamination sources reducing public health risks. Astill et al. (2019) emphasized blockchain's utility in verifying compliance with safety standards, such as HACCP, through tamper-proof logs. Kamilaris et al. (2019) further noted that blockchain-enabled traceability systems empower consumers to verify product authenticity, fostering trust in organic or ethically sourced goods. For instance, a study by Gartner (2020) found that blockchain-based systems can reduce the time and cost of tracing the point of origin of food products, thereby reducing the risk of foodborne illnesses through early warning systems and improving food safety. A study by IBM (2020) highlighted that blockchain reduces traceability time from days to seconds, which is critical during outbreaks like E. coli in leafy greens. Rapid traceability prevents the widespread distribution of unsafe products, directly protecting consumer health (FDA, 2019). Similarly, another case study by IBM (2020) showcased how the supply chain of salmon was tracked using blockchain technology, enabling consumers to verify the authenticity and sustainability of the product.

Blockchain improves food safety by enabling end-to-end traceability. Each transaction, from farm to retailer, is recorded in real-time, creating an auditable trail. Quality control in food supply chains requires continuous monitoring of environmental conditions, handling practices, and product integrity. Blockchain integrates IoT sensors and RFID tags to capture real-time temperature, humidity, and contaminant exposure data. For example, Astill et al. (2019) highlight how IoT-enabled blockchain systems track perishable goods like dairy and meat, ensuring adherence to cold chain requirements. Deviations trigger automated alerts, enabling immediate corrective actions to prevent spoilage (Tian, 2016). In another instance, IoT sensors integrated with blockchain can monitor temperature and humidity during transportation, ensuring compliance with safety standards (Kshetri, 2018). This granular tracking allows swift identification of contaminated products.

During product recalls, blockchain's transparency ensures all stakeholders access unified data, enabling targeted removals of affected batches. Smart contracts automate recall triggers, alerting retailers and regulators immediately upon contamination detection (Saberi et al., 2019). This precision minimizes over-recall, preserving brand trust and reducing costs. The FAO (2019) estimates that blockchain could reduce recall expenses by 30% as companies avoid broad-spectrum recalls.

By ensuring real-time access to environmental and handling data, blockchain supports proactive quality control and facilitates compliance with international food safety standards. Smart contracts enable automated recall processes, reducing public health risks and economic losses (Chen et al., 2021; Astill et al., 2019). The ability to swiftly isolate and remove compromised products is especially valuable during foodborne illness outbreaks, as evidenced by recent case studies (FDA, 2019).

C. Economic and Sustainability Implications

Blockchain streamlines supply chain operations by reducing administrative delays, minimizing fraud, and automating processes via smart contracts. Kamble et al. (2020) highlight that BCT eliminates intermediaries, enabling direct transactions between farmers, distributors, and retailers. Smart contracts automate payment settlements and compliance checks, reducing processing times by up to 80% in pilot projects (Queiroz & Wamba, 2019). For example, using a blockchain-based system, Walmart reduced the time it took to trace food origins from days to seconds (IBM, 2020).

Blockchain aggregates historical and real-time data across supply chain nodes, enhancing demand forecasting accuracy. Saberi et al. (2019) argue that BCT's decentralized data-sharing framework supports machine learning models for predicting consumer demand. Decentralized platforms like TE-FOOD employ blockchain to analyze purchasing patterns, enabling dynamic inventory adjustments (Treiblmaier, 2018). Visible impacts include reduced waste through accurate forecasts, lowering overproduction and spoilage (FAO, 2019), and responsive supply chains where retailers adjust orders based on real-time sales data (Kshetri, 2018).

The key benefits include reduced costs as automation lowers labor and administrative expenses (Kshetri, 2018); benefits also include improved trust since the immutable records ensure data integrity, reducing disputes (Tian, 2016).

Researchers have explored blockchain's role in advancing sustainability goals. Saberi et al. (2019) identified its capacity to incentivize ethical practices by transparently recording certifications (e.g., Fair Trade). Kouhizadeh et al. (2021) highlighted blockchain's environmental benefits, such as reducing food waste through optimized inventory management and carbon footprint tracking. Kamble et al. (2020) proposed a framework integrating blockchain with AI and IoT, showing improved predictive analytics for demand forecasting and resource allocation.

Integrating BCT with IoT sensors and RFID tags enhances the real-time monitoring of food products. In an agricultural case study, Tian (2016) demonstrated that blockchain-enabled IoT systems provide end-to-end visibility, reducing spoilage and optimizing inventory management. For instance, sensors track temperature and humidity during transportation, logging data on the blockchain to ensure compliance with safety standards. This real-time tracking minimizes stockouts and overstocking, improving resource allocation (Kouhizadeh & Sarkis, 2018). Blockchain technology can potentially streamline processes and reduce costs in FSCM by eliminating intermediaries and using smart contracts to automate transactions (Christidis & Devetsikiotis, 2016).

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A study by Deloitte (2018) found that blockchain-based supply chain management systems can reduce administrative costs by up to 30% by reducing the need for manual data entry and eliminating paper-based processes. Additionally, blockchain can advance inventory management by using real-time data on product availability to control stockouts and overstocking. Industrial application examples include IBM Food Trust: Partners like Nestlé and Carrefour use blockchain to trace products like mangoes and milk, cutting recall times by 90% (IBM, 2020). Retailers like Carrefour implemented the IBM Food Trust; this platform tracks products like chicken, ensuring real-time data sharing. Carrefour reported a 28% increase in customer trust post-implementation (IBM, 2020). Walmart's Pork Tracking in China traced pork slices to their source in seconds, showcasing blockchain's scalability (Kamath, 2018). Blockchain reduces administrative overheads by eliminating intermediaries and automating processes. Waste reduction and improved inventory management also contribute to economic and environmental sustainability, aligning with global sustainability goals (Kamble et al., 2020; Kouhizadeh & Sarkis, 2018).

D. Adoption Challenges of BCT in FSCM

The adoption of blockchain technology in FSCM is not without challenges despite its potential benefits. The following barriers hinder widespread blockchain adoption in FSCM:

- *Technical Complexity and Scalability*

The technical complexity of implementing and maintaining blockchain systems is among the significant challenges. There are concerns about blockchain technology's scalability, interoperability, and energy consumption (Bonneau et al., 2016). Integrating blockchain with existing IT infrastructure can be costly and time-consuming, particularly for small and medium-sized enterprises (SMEs) that may lack the necessary technical expertise (Kshetri, 2018). Describing organizational hurdles, Kshetri (2018) noted scalability issues, especially the energy-intensive consensus mechanisms such as Proof-of-Work, as impractical for large-scale supply chains. PoW blockchains, notably Bitcoin, consume vast amounts of energy. Vranken (2017) estimates that Bitcoin's annual energy use rivals that of small countries. Buterin (2021) advocates transitioning to PoS, as Ethereum has done, to reduce environmental impact. For example, energy consumption associated with blockchain mining, particularly in proof-of-work (PoW) based systems, has raised environmental concerns (Stoll et al., 2019).

Integration with legacy systems remains challenging, and energy-intensive consensus mechanisms such as PoW pose scalability concerns (Croman et al., 2016; Vranken, 2017). Blockchain networks face scalability issues; Bitcoin processes only seven transactions per second (tps), compared to Visa's 24,000 tps (Croman et al., 2016). Solutions like dividing the network into smaller segments and layer-2 protocols aim to address this (Zhang & Lee, 2020). While alternative consensus mechanisms, such as proof-of-stake (PoS), have been proposed to address these issues, their adoption in FSCM is still limited.

- *Regulatory and Legal Challenges*

The absence of clear regulatory frameworks complicates cross-border compliance and data privacy issues (Kshetri, 2018; Catalini & Gans, 2020). Due to fragmented documentation and auditing processes, compliance with food safety regulations (e.g., FDA's FSMA, EU's General Food Law) is a persistent challenge. Regulation for blockchain technology is still evolving, and there is a lack of clarity regarding the legal implications of its adoption in FSCM. Issues such as data privacy, intellectual property rights, and liability in the case of fraud or data breaches need to be addressed (Kshetri, 2018). Additionally, the cross-border nature of food supply chains adds complexity to regulatory compliance, as different countries may have different regulations regarding blockchain and food safety. Regulatory uncertainty persists, with governments struggling to classify cryptocurrencies and enforce cross-border compliance. Catalini and Gans (2016) emphasize the need for frameworks balancing innovation and consumer protection. Werbach (2018) warns that overly restrictive policies could stifle blockchain's potential.

- *Industry-Wide Collaboration*

Effective blockchain implementation requires consensus among diverse stakeholders, which is often impeded by competitive dynamics and data-sharing concerns (Accenture, 2018; Galvez et al., 2018). The success of blockchain in FSCM depends on the willingness of all supply chain participants to adopt and collaborate on the platform. However, achieving industry-wide collaboration can be challenging due to competitive dynamics, data-sharing concerns, and the lack of a standardized framework for blockchain adoption (Paliwal et al., 2020). For example, a study by Accenture (2018) found that 73% of supply chain executives believe blockchain will require significant collaboration among industry players, but only 32% are confident in collaborating effectively. Galvez et al. (2018) identified resistance from stakeholders accustomed to centralized systems, compounded by a lack of regulatory frameworks. Caro et al. (2018) also stressed the interoperability challenges between blockchain platforms and legacy IT systems. Diverse blockchain platforms (e.g., Hyperledger, Ethereum) and legacy systems struggle to integrate, hindering seamless data sharing (Feng et al., 2020). Additionally, interoperability between disparate blockchain systems is critical for global supply chains but remains underdeveloped (Feng et al., 2020). Legacy systems struggle to integrate with blockchain (Kouhizadeh et al., 2021).

E. Critical Evaluation

While literature illustrates numerous benefits, most studies are still at a conceptual or pilot stage. Longitudinal research is needed to evaluate blockchain's long-term impact on FSCM performance. Integrative approaches that combine blockchain with AI, IoT, and digital twins could address these limitations, yet such hybrid systems require further

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empirical validation (Franco et al., 2020; Rejeb et al., 2020). While the literature highlights the potential benefits of blockchain in FSCM, there is a need for more empirical evidence to support its widespread adoption. Many studies are still at the conceptual or pilot stage, and there is limited research on the long-term impact of blockchain on FSCM performance. Despite its potential, blockchain faces adoption barriers. Small-scale farmers and SMEs often lack the resources and infrastructure to integrate blockchain, risking exclusion from modern supply chains and exacerbating inequalities in supply chains (Kshetri, 2018). Saberi et al. (2019) posit that initial implementation expenses deter small suppliers. Furthermore, the challenges associated with blockchain adoption, such as technical complexity and regulatory uncertainty, must be carefully considered before implementing blockchain-based solutions.

Data integrity remains another concern; inaccurate initial data inputs undermine blockchain's reliability, and errors from faulty sensors or manual inputs compromise reliability (Tian, 2016). Furthermore, regulatory fragmentation exists as global supply chains face conflicting national regulations, complicating blockchain's standardization (Treiblmaier, 2018). Scalability is also challenging as high energy consumption and slow transaction speeds limit large-scale use (Zheng et al., 2020).

VI. LIMITATIONS AND IMPLICATIONS FOR PRACTICE

This review is limited by the predominance of conceptual studies in current literature, highlighting the need for more robust empirical research. For practitioners, the findings suggest that while blockchain offers substantial benefits regarding traceability and transparency, its successful implementation depends on overcoming technical and regulatory challenges. Therefore, policymakers and industry leaders must collaborate to develop standardized frameworks that facilitate blockchain integration across diverse supply chain networks.

VII. CONCLUSIONS

Blockchain technology has the potential to revolutionize FSCM by enabling end-to-end transparency, enhancing food safety, and reducing operational inefficiencies. However, transitioning from pilot projects to full-scale implementation requires addressing significant technical, regulatory, and collaborative barriers. This review highlights the necessity for interdisciplinary research and cross-sector collaboration to realize blockchain's transformative potential in FSCM. Blockchain technology can revolutionize food supply chain management by enhancing transparency, traceability, and efficiency. However, its adoption is not without challenges, including technical complexity, regulatory uncertainty, and the need for industry-wide collaboration. BCT offers significant benefits for food supply chains, including improved traceability, safety, and sustainability. However, widespread adoption requires addressing technical limitations, stakeholder resistance, and regulatory gaps. Future research should focus on scalable, interoperable solutions and empirical studies on real-world implementations. BCT offers robust solutions for quality control and compliance in food supply chains, enhancing transparency and reducing risks. Although challenges like data integrity and interoperability persist, collaborations between governments, tech firms, and producers such as IBM Food Trust and EU GI initiatives demonstrate their potential. Future efforts should prioritize scalable, inclusive designs to ensure equitable benefits across the supply chain ecosystem. Blockchain significantly enhances food supply chain efficiency by enabling real-time tracking and data-driven forecasting. While challenges remain, its integration with IoT and AI promises to reduce waste, lower costs, and improve responsiveness. Collaborative efforts among stakeholders are critical to overcoming technical and economic barriers.

Blockchain revolutionizes food supply chains by ensuring safety and efficient recalls. Through case studies and technological integration, it demonstrates significant potential to safeguard public health and reduce economic waste. Widespread adoption, however, requires industry collaboration and standardization. BCT significantly enhances traceability and provenance in food supply chains, fostering transparency and trust. While challenges like adoption barriers and data integrity persist, ongoing advancements and collaborations (e.g., IBM Food Trust) highlight their transformative potential. Future research should address scalability and inclusivity to ensure equitable benefits across the supply chain.

RECOMMENDATIONS AND FUTURE RESEARCH AGENDA

➢ *Recommendations*

- Empirical Validation: Longitudinal and large-scale empirical studies should be conducted to quantify blockchain's impact on cost savings, efficiency, and food safety outcomes.
- Technological Integration: Hybrid systems integrating blockchain with IoT, AI, and digital twins should be explored to enhance predictive analytics and operational efficiency.
- Regulatory Frameworks: Standardized regulatory guidelines should be developed to harmonize blockchain applications across international food supply chains.
- Stakeholder Collaboration: Collaborative initiatives among industry players, governments, and technology providers should be fostered to create interoperable blockchain systems.
- SME Accessibility: Strategies to lower SMEs' barriers to adopting blockchain technology should be investigated to ensure equitable benefits across the supply chain.

➢ *Future Research Agenda*

The outcome of this comprehensive review suggests that future studies should focus on:

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- Evaluating the long-term performance of blockchain-enabled FSCM systems through field experiments and case studies.
- Investigating energy-efficient consensus algorithms and scalable blockchain architectures.
- Examining the socio-economic impacts of blockchain adoption, particularly regarding SME inclusion and consumer trust.
- Integrating blockchain with emerging technologies to create adaptive, resilient, and sustainable supply chain networks (Casino et al., 2019; Rejeb et al., 2020).

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