BLOCKCHAIN ADOPTION IN SUPPLY CHAINS: A COMPREHENSIVE LITERATURE REVIEW ON CONSUMER PREFERENCE, GREEN PRACTICES, AND COMPLIANCE APPLICATIONS

S. SRINIVASAN
Research Scholar
Kongunadu Arts and Science College (Autonomous), Coimbatore-641029.

Dr. R. SARAVANA MOORTHY
Associate Professor and Head,
Department of Computer Science (SF)
Kongunadu Arts and Science College (Autonomous), Coimbatore-641029.

Abstract

The integration of blockchain technology in supply chain management has shown promising potential for enhancing transparency, traceability, and operational integrity. However, limited attention has been paid to the strategic implications of different blockchain tracing configurations in multi-echelon supply chains. This study proposes a novel framework that categorizes blockchain adoption into four distinct modes based on tracing focus—product-level or component-level—and the authority responsible for block generation—supply chain members or transportation links. A mixed-integer linear programming (MILP) model is developed to simultaneously optimize supply chain design, green product flow, and blockchain configuration under cost, transparency, and service-level objectives. To evaluate the relative performance of each adoption scenario, the study introduces a hybrid Branch and Efficiency (B&E) algorithm that combines MILP with Simultaneous Data Envelopment Analysis (SDEA). Computational results demonstrate significant trade-offs between transparency and operational costs, providing critical insights into the optimal deployment of blockchain in sustainable two-echelon supply chains. The findings offer a quantitative decision-making tool for practitioners seeking to strategically implement blockchain under economic and environmental constraints.

Keywords: Blockchain Technology, Two-Echelon Supply Chain, Product Tracing, Component Tracing, Block-Generating Authority, Green Supply Chain Management (GSCM), Mixed-Integer Linear Programming (MILP), Branch and Efficiency (B&E) Algorithm, Simultaneous Data Envelopment Analysis (SDEA)

I. Introduction

In recent years, blockchain technology has emerged as a transformative force across various sectors, offering unprecedented levels of transparency, traceability, and security in data management. Among its many applications, the deployment of blockchain in supply chain management (SCM) has attracted significant scholarly and industrial interest due to its potential to eliminate information asymmetry, enhance trust among stakeholders, and streamline complex transactional networks. These benefits are especially critical in the context of green supply chains, where environmental accountability and product authenticity are becoming increasingly essential.

Despite growing interest, the practical implementation of blockchain in multi-echelon supply chains—particularly those involving environmentally sustainable practices—remains challenging. One key area of ambiguity is the scope and architecture of blockchain tracing. While some systems implement product-level tracing, recording the entire journey of goods from origin to end-user, others focus on component-level tracing, capturing the transactional exchanges between individual supply chain actors. The selection between these approaches has direct implications for cost, transparency, data granularity, and operational complexity.

Moreover, blockchain adoption also involves strategic decisions regarding who should generate and maintain the blockchain blocks—whether supply chain members (e.g., manufacturers, warehouses, retailers) or the transportation links (e.g., logistics providers). These architectural choices influence not only the level of traceability but also the cost structure, network performance, and stakeholder trust within the supply chain.

While prior research has primarily explored blockchain adoption through conceptual or case-specific lenses, there remains a significant gap in quantitative models that guide supply chain designers on how to deploy blockchain most effectively. In particular, there is limited understanding of how product versus component tracing, and member- versus link-based block generation, affect supply chain performance under cost, service, and transparency considerations.

To address this gap, the present study proposes a novel classification framework for blockchain adoption and develops a mixed-integer linear programming (MILP) model to optimize green supply chain operations under various blockchain configurations. In addition, a new Branch and Efficiency (B&E) algorithm is introduced, combining the MILP model with Simultaneous Data Envelopment Analysis (SDEA) to evaluate the trade-offs among competing objectives. Through computational experiments, the study offers strategic insights into how firms can balance economic efficiency, traceability, and sustainability when adopting blockchain technology in two-echelon supply chain networks.

II. Supply Chain and Blockchain Technology: Background, Definition and Motivation

The integration of energy-efficient technologies (EET) in food supply chains (FSCs) is increasingly recognized as a strategic imperative for achieving sustainability and reducing environmental impact. Recent literature emphasizes the critical role of EETs—including renewable energy systems, blockchain, IoT, and AI—in optimizing operations across production, transportation, storage, and distribution phases of the FSC. Studies have demonstrated that technologies such as blockchain enhance traceability, transparency, and accountability within supply chains by enabling immutable tracking of energy inputs and outputs. This contributes to more efficient energy use and reinforces consumer trust in sustainable food practices. However, despite the technological promise, consumer adoption of EET-driven solutions remains limited, primarily due to factors like cost sensitivity, perceived complexity, and lack of awareness. Several researchers have explored consumer intention toward EET-FSC, highlighting influences such as perceived benefits, environmental consciousness, trust in technology, and socio-economic status. For instance, Baldi et al. (2021) underscored the significance of perceived environmental and economic benefits, while Nunes and Deliberador emphasized regional and cultural variations. However, these works typically relied on traditional methodologies such as surveys and regression analysis, which often fall short in capturing the complex, nonlinear relationships inherent in consumer behavior. To address this limitation, recent studies have turned to machine learning (ML) approaches, which offer enhanced capabilities for modeling large-scale and diverse consumer datasets. ML techniques—such as Random Forest, k-NN, and Neural Networks—enable more nuanced predictions of consumer behavior by integrating demographic, behavioral, and psychographic variables. These models surpass traditional methods in detecting hidden patterns and providing actionable insights. Despite the advances, the literature still lacks comprehensive, empirically-driven models that predict consumer willingness to adopt EETs in the context of food systems. This gap has prompted a shift toward hybrid frameworks combining ML with behavioral modeling, aiming to inform more effective policy design, marketing strategies, and technology implementation across the FSC. [1]

Blockchain technology has emerged as a transformative tool in supply chain management, primarily due to its ability to enhance information transparency, ensure product authenticity, and improve consumer trust. Recent research has explored its integration across various supply chains—including food, pharmaceutical, fashion, and automotive sectors—highlighting its potential to mitigate issues of quality misrepresentation and reduce reliance on traditional quality inspection methods. A key contribution of the study by Ma et al. (2025) lies in examining the intersection of blockchain adoption and consumer quality preferences. While earlier works (e.g., Xu & Choi, 2021; Zhang et al., 2022) evaluated blockchain from the manufacturer's implementation perspective, this research shifts focus toward retailer-led blockchain deployment, which reflects current market practices where large platforms like JD.com and Walmart drive adoption to ensure traceability and compliance. Previous studies have often treated consumers as homogenous entities—either in favor of blockchain-based transparency or indifferent to it. In contrast, this study introduces a more nuanced view by segmenting consumers into quality-conscious and quality-indifferent groups, thus accounting for heterogeneity in perceived blockchain value. This segmentation allows a more realistic analysis of blockchain's impact on consumer utility and supply chain decisions. Another novel aspect is the comparison between two prevalent e-commerce business models: the wholesale price model and the marketplace model. Prior literature (e.g., Abhishek et al., 2016; Ha et al., 2022) has examined these structures primarily in relation to commission dynamics and pricing strategies. However, Ma et al. extend the analysis to evaluate how blockchain adoption alters optimal pricing, retailer-manufacturer dynamics, and overall profitability under each model. Their findings suggest that blockchain reduces the influence of commissions in pricing decisions and enables higher consumer willingness to pay when quality transparency is valued. Importantly, the study also integrates consumer privacy concerns and the heterogeneity in blockchain utility perception, offering a realistic assessment of blockchain's limitations. It highlights that while blockchain enhances consumer surplus under certain conditions, excessive privacy concerns or low product quality may limit its perceived value.

In sum, the study advances existing literature by:

- Shifting focus to retailer-led blockchain strategies
- Introducing consumer heterogeneity in quality preferences
- Comparing supply chain performance across business models with and without blockchain
- Considering consumer privacy trade-offs in adoption decisions

These insights are crucial for researchers aiming to understand the complex dynamics between technology adoption, business strategy, and consumer behavior in digitally enhanced supply chains. [2]

The increasing environmental impact of industrial supply chains has catalyzed the emergence of green supply chain management (GSCM) as a critical area of academic and practical interest. GSCM integrates environmental thinking into traditional supply chain management, encompassing product design, sourcing, production, delivery, and end-of-life processes. Numerous studies have highlighted the necessity of sustainable practices and the challenges posed by their integration in competitive markets characterized by complex dynamics and uncertainty.

A significant body of literature has addressed various components of green supply chains. For instance, Hsu et al. (2013) and Diabat et al. (2011) explored structural models for GSCM adoption, emphasizing decision hierarchies and key drivers, while Olugu et al. (2011) developed performance metrics to evaluate green initiatives. However, these approaches often assumed deterministic market conditions, neglecting the role of demand uncertainty and the dynamics of consumer trust, especially concerning green product claims.

To enhance supply chain transparency and mitigate information asymmetry, researchers have increasingly explored the role of blockchain technology. Blockchain has been praised for its ability to provide immutable transaction records, improve traceability, and facilitate trust among stakeholders. Studies by Banerjee (2018), Saberi et al. (2019), and Chang et al. (2020) have outlined conceptual frameworks for blockchain-enabled supply chains, identifying both opportunities and adoption barriers across industries.

However, the integration of blockchain into green supply chains remains underexplored, particularly in the context of consumer skepticism toward environmental claims. This study responds to that gap by examining how blockchain can reduce green uncertainty—a term used to describe consumers' hesitation to accept unverified green product information. It extends previous research by combining blockchain technology with game-theoretic models and dynamic system analysis to capture the effects of consumer preferences, demand fluctuations, and investment strategies in a competitive duopoly.

The literature also acknowledges the complexity of green supply chains, particularly when viewed as dynamic systems. Scholars such as Wilding (1998) and Singh et al. (2016) examined the non-linear and often chaotic nature of supply chains, which can be exacerbated by external shocks or decision-making delays. This study builds on those insights by introducing delay feedback control mechanisms to stabilize supply chain behavior, offering a novel contribution to the literature on green supply chain dynamics. [3]

The global halal market has experienced significant growth, driven by increasing demand for ethical, safe, and religiously compliant food products. In response, scholars and practitioners have investigated mechanisms to strengthen halal certification processes and supply chain integrity. However, the complexity and fragmentation of halal standards, coupled with a lack of global harmonization, present major challenges for halal stakeholders worldwide.

Previous literature identifies multiple barriers to halal compliance, particularly in Asian markets where halal food consumption is rising. These include low awareness of halal requirements, inconsistent regulatory frameworks, ingredient scarcity, and difficulties in tracing product provenance across international and multi-party supply chains. Scholars such as Tieman (2011) and Shafie & Othman (2006) have emphasized the importance of end-to-end halal assurance, yet existing systems often rely on manual, paper-based processes prone to errors and fraud.

To address these challenges, recent research has turned to emerging digital technologies, particularly blockchain and artificial intelligence (AI). Blockchain offers a decentralized and immutable ledger ideal for documenting product history, certifying authenticity, and enhancing traceability across complex halal supply chains. Studies by Tan & Ngah (2020) and Rejeb et al. (2018) demonstrate blockchain's ability to improve credibility and accountability, particularly in verifying slaughtering methods, handling practices, and ingredient sourcing.

Concurrently, AI is being explored for its ability to automate compliance checks, detect irregularities, and support risk management. Applications include knowledge graphs for representing halal rules and relationships, machine learning for ingredient classification, and natural language processing for label verification. These techniques support real-time validation and reduce human error, a key concern in traditional certification models.

Despite these advances, prior works tend to focus narrowly on either blockchain or AI, often presenting conceptual benefits without fully integrated frameworks or real-world case studies. Moreover, there is limited attention to explainable AI, which is crucial for transparency in religiously sensitive domains like halal compliance.

Sunmola et al. (2025) address this gap by proposing a holistic, integrated framework that combines blockchain and AI for halal compliance. Their approach includes a layered architecture supporting product validation, production process verification, and logistics oversight, facilitated by smart contracts and explainable AI components such as knowledge graphs. This framework builds on earlier models by incorporating real-time decision-making, enhanced data integrity, and multi-stakeholder trust through automation and transparency. [4]

The growing complexity and data-centric nature of the healthcare supply chain (HSC) have led to increased interest in digital transformation through technologies such as Artificial Intelligence (AI) and Blockchain. These technologies are recognized for their potential to enhance transparency, data security, decision-making accuracy, and operational efficiency in the healthcare ecosystem.

AI has been widely explored in healthcare for its applications in diagnostics, personalized treatment, drug discovery, and clinical decision support. Numerous studies have examined how AI facilitates real-time analytics, pattern recognition, and disease prediction. Jiang et al. (2022) and Rong et al. (2023) highlighted AI's ability to aid in stroke diagnosis and biomedical research, while Davenport and Kalakota emphasized AI's impact on automating clinical tasks and reducing healthcare costs. However, the implementation of AI faces challenges including interpretability, data privacy concerns, and ethical dilemmas, as noted by Gerke et al. and Lee & Yoon.

Blockchain has emerged as a critical technology to address issues of data security, integrity, and traceability in healthcare systems. Its decentralized, immutable ledger is particularly valuable in maintaining trustworthy electronic health records (EHRs), ensuring authenticity in pharmaceutical supply chains, and preventing fraud in insurance and clinical trials. Miyachi et al. proposed blockchain frameworks for healthcare privacy, while Chelladurai et al. and Shoaib et al. explored blockchain applications in EHR and identity management. Yet, limitations related to scalability, interoperability, and public acceptance remain barriers to widespread adoption.

Recent scholarship has moved toward the synergistic integration of AI and blockchain to create intelligent, secure, and autonomous healthcare systems. Studies by Xie et al., Rao et al., and Mamushina et al. emphasize how AI enhances the decision-making capabilities of blockchain systems, while blockchain provides a secure and transparent foundation for managing health data used by AI algorithms. These integrated systems are proposed for applications ranging from chronic disease monitoring to biomedical data marketplaces and decentralized diagnostic systems. However, despite this momentum, few studies systematically prioritize the critical success factors for AI-blockchain integration in the healthcare supply chain. [5]

The acceleration of digital transformation and the emergence of the metaverse as a business environment have opened new opportunities for small and medium-sized enterprises (SMEs) to improve sustainable business performance (SBP). However, SMEs often face challenges in understanding and implementing these advanced technologies effectively. Recent scholarship has focused on two core enablers of digital transformation in SMEs—Artificial Intelligence (AI) and Blockchain Technology (BCT)—and their role in enhancing supply chain efficiency, transparency, and resilience.

AI technologies are widely recognized for enabling firms to process complex data, automate decision-making, and respond rapidly to environmental uncertainties. Prior studies have established AI's effectiveness in demand forecasting, risk management, and process optimization, thereby contributing to supply chain resilience (SCR). AI can help detect supply chain disruptions, improve inventory visibility, and streamline operations, especially in times of crisis such as the COVID-19 pandemic. However, existing literature often examines AI in isolated contexts without fully exploring its synergistic role within a broader digital ecosystem.

Blockchain has garnered significant attention for its ability to provide secure, immutable, and transparent record-keeping across the supply chain. In previous works, BCT has been associated with enhanced trust, traceability, and data visibility, which are vital for regulatory compliance and sustainability reporting. Blockchain also supports smart contract automation and fraud prevention, strengthening organizational accountability. Despite these advantages, SMEs often encounter cost-related and technical barriers in adopting blockchain technologies, which restrict their scalability and practical application.

The literature on Closed-Loop Supply Chains (CLSC) highlights their importance in minimizing waste and maximizing resource recovery throughout the product life cycle. CLSC models integrate forward and reverse logistics and are increasingly aligned with sustainability and circular economy principles. Research has shown that CLSC adoption can promote environmental performance and reduce operational costs. However, the implementation of CLSC in SMEs is constrained by technological limitations, resource scarcity, and lack of strategic direction—areas where digital technologies like AI and BCT could play a transformative role.

Despite growing recognition of the benefits of AI, BCT, and CLSC, limited studies have explored their integrated impact on SMEs—particularly within the context of the metaverse. The metaverse, still in its formative stage in supply chain research, is seen as a virtual space where digital technologies converge to enhance organizational performance. Khan et al. address this critical gap by applying Organizational Information Processing Theory (OIPT) to develop a comprehensive framework that links AI and BCT with SCR, CLSC, and SBP. This theoretical integration enables a better understanding of how SMEs can leverage emerging technologies to develop adaptive capabilities (ACs), improve decision-making, and drive sustainable transformation. [6]

In recent years, the adoption of blockchain technology in supply chain management has emerged as a promising strategy to improve transparency, traceability, and trustworthiness across complex supply networks. While blockchain has gained significant traction in domains like cryptocurrency and finance, its integration into supply chain optimization, especially green and sustainable supply chains, remains underexplored.

Earlier research by Dutta et al. (2020), Jabbar et al. (2021), and Shah et al. (2021) emphasized the potential of blockchain to enhance information security, traceability, and data integration in diverse supply chain sectors, including food, healthcare, and energy. These studies generally provide conceptual frameworks or case-specific applications, outlining both technical and managerial barriers to implementation. Meanwhile, scholars such as Li et al. (2022) and Kumar et al. (2022) have shown that blockchain can reinforce supply chain resilience and sustainability by reducing information asymmetry and enabling decentralized data sharing.

However, a significant gap persists in the quantitative modeling of blockchain adoption strategies, especially within multi-echelon supply chains. Most existing works either focus on qualitative assessments, employ multi-criteria decision-making (MCDM) techniques to identify adoption barriers (e.g., Yadav & Kumar, 2022), or analyze case-specific blockchain use cases in traceability and regulatory compliance. Few studies have attempted to formulate and solve mathematical optimization problems that incorporate blockchain costs, configuration complexity, or transparency metrics.

This gap is particularly evident in the context of Green Supply Chain Management (GSCM). Despite increasing attention to carbon footprint tracking and eco-friendly logistics, there is limited research on how blockchain can be strategically embedded into green supply chains. Existing studies also lack clarity on whether blockchain adoption should focus on end-to-end product tracing or component-level tracing between supply chain entities.

The study by Babaei et al. (2025) addresses this void by developing a novel classification and optimization framework that differentiates between two fundamental modes of blockchain integration. In Product Tracing, it’s recording the complete lifecycle of green products across the entire supply chain. Like that Component Tracing also Capturing transaction-level data and interactions between specific supply chain members or transportation links.

To support this classification, the authors propose four distinct adoption scenarios based on who has the authority to generate blockchain blocks—either supply chain members (nodes) or transportation links. This taxonomy allows a systematic comparison of blockchain deployment costs, transparency outcomes, and operational efficiency.

Moreover, the paper employs Mixed-Integer Linear Programming (MILP) models to optimize supply chain design under different blockchain configurations and uses an innovative Branch and Efficiency (B&E) algorithm coupled with Simultaneous Data Envelopment Analysis (SDEA) to evaluate trade-offs among cost, service, and transparency. [7]

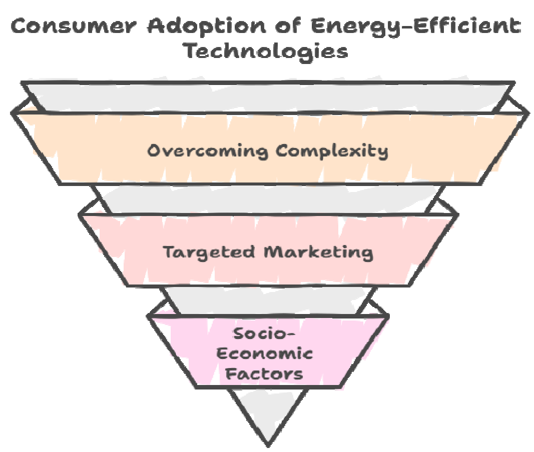
Paper Title	Research Methodology	Tools/Models Used	Data Source	Focus Area
Consumer Quality Preference	Analytical modeling	Game theory; mathematical modeling	Theoretical (no empirical data)	Blockchain impact on pricing, quality preference in supply chains
Dynamic Analysis in EcoGreen	Theoretical and simulation	Game theory; dynamic system modeling	Simulated data & theoretical models	Blockchain and demand uncertainty in green supply chains
Food Supply Chain	Empirical & predictive modeling	Machine Learning (Random Forest, ARM)	Primary survey data	Consumer intention for adopting energy-efficient tech in FSC
Halal for Holistic Framework	Conceptual framework & illustrative example	AI integration, knowledge graphs, smart contracts	Literature synthesis & case-based illustration	Blockchain-AI framework for Halal compliance
Healthcare	Multi-criteria decision-making (MCDM)	Fuzzy AHP & Fuzzy DEMATEL	Literature review + expert judgment	Evaluating AI-integrated blockchain in healthcare supply chains
MSME	Structural equation modeling (SEM)	PLS-SEM	Survey (326 SMEs)	AI and blockchain's impact on sustainable development in SMEs
Product & Component Tracing	Optimization modeling	MILP, Branch & Efficiency, SDEA	Simulated numerical scenarios	Blockchain adoption in green supply chain tracing methods

III. Main Findings, Challenges and Future Research Directions

Despite the growing interest in sustainable practices within the food supply chain (FSC), the adoption of energy-efficient technologies (EETs) remains constrained by several critical challenges. One of the foremost issues is limited consumer awareness and engagement. The study revealed a prevalent *neutral attitude* among consumers, particularly in the middle-income bracket (₹50,000–₹1,00,000 per month), toward technologies such as blockchain when applied to energy efficiency. This suggests a lack of targeted education and communication regarding the potential benefits of EETs.

Technological complexity also emerged as a significant barrier. While blockchain and IoT offer immense value in enhancing transparency and traceability, their abstract nature and perceived inaccessibility often discourage adoption, especially among consumers with limited digital literacy. Rural populations and individuals with lower education levels were more likely to exhibit skepticism or indifference, exacerbated by a lack of localized awareness campaigns and practical demonstrations of these technologies.

Furthermore, the absence of tailored marketing strategies has contributed to the disconnect between sustainable product offerings and consumer intention. The research indicates that many consumers are not exposed to the value proposition of EETs in relatable or actionable terms. Additionally, socio-economic factors, such as income disparity and geographical segmentation, play a critical role in shaping consumer preferences. Urban, younger, and more educated individuals were found to be more receptive to EET-driven supply chains, while older and rural consumers remained hesitant or uninformed. These challenges highlight the need for more nuanced, data-informed approaches that account for consumer diversity and the complex interplay between behavioral, demographic, and contextual factors influencing technology adoption in FSCs. To investigate consumer intention and willingness to adopt energy-efficient technologies in the food supply chain, the study employed a predictive modeling framework underpinned by machine learning (ML) and data mining techniques. The methodology was structured into the following key stages.



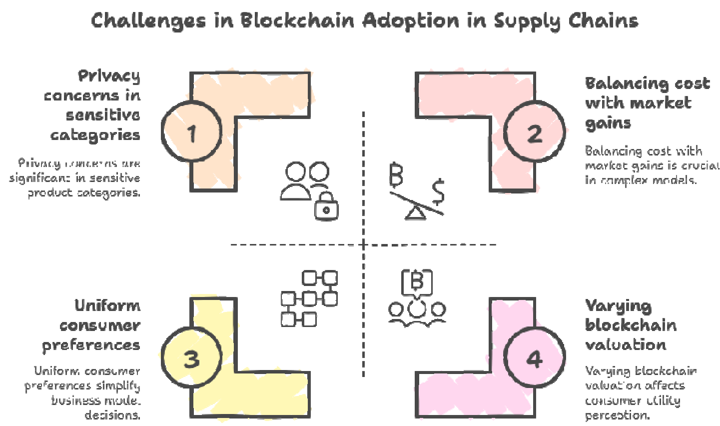
Primary data were obtained via a structured online survey targeting grocery consumers across various regions in India. A total of 433 responses were collected, encompassing a diverse demographic spread. The questionnaire captured detailed information on income levels, geographic location, dietary preferences, shopping habits, and perceptions of blockchain technology and sustainability. Efforts were made to ensure sample diversity through distribution via social media, email lists, and forums focused on sustainable food consumption.

The raw dataset underwent comprehensive preprocessing, including the handling of missing values, encoding of categorical features, and normalization of numerical variables. To address potential class imbalances, class distribution analysis was conducted, and data sampling was executed using a 70:30 train-test split, complemented by 20-fold cross-validation to enhance model generalizability.

Association Rule Mining was applied to uncover latent patterns and associations between demographic variables and consumer interest in EET-FSC. Key metrics such as support, confidence, and lift were used to evaluate rule strength and prevalence. ARM revealed several significant patterns, including the influence of income, regional factors, and FSC transparency perceptions on blockchain awareness and EET interest. The Random Forest model demonstrated the highest classification accuracy (82%) and balanced performance across various metrics, making it the most reliable model for predicting consumer intention. The models were assessed using multiple performance indicators, including Accuracy, Precision, Recall, F1-Score, Area Under the Curve (AUC) and Matthews Correlation Coefficient (MCC). Additional evaluations involved ROC analysis and calibration plots to validate model robustness and predictive calibration. The Wilcoxon Signed-Ranks Test was applied to statistically compare performance differences among the models. The Orange Data Mining platform was used for implementing the machine learning models and visualizing the results, offering an intuitive interface for exploratory data analysis and predictive modeling.

[2] Despite the increasing integration of blockchain technology in supply chains, several critical challenges persist, particularly when considering consumer quality preferences and business model dynamics. First, one of the most fundamental challenges lies in consumer heterogeneity. Not all consumers value blockchain-enabled transparency equally. The market comprises both quality-conscious and quality-indifferent consumers, and this divergence significantly affects the perceived utility of blockchain. Previous models often oversimplified consumer behavior by treating preferences as binary or uniform, but this study reveals that even among quality-sensitive consumers, the marginal valuation of blockchain varies considerably. Second, privacy concerns create a barrier to blockchain adoption. While blockchain enhances traceability and transparency, it may also introduce apprehensions related to data security and consumer anonymity, particularly in sensitive product categories. These concerns can offset the perceived benefits of improved product information. Third, economic feasibility remains a pressing issue. Implementing blockchain incurs costs at multiple levels—technological integration, data management, and training—which may not always be justified by increased sales or consumer engagement. For retailers and manufacturers, balancing blockchain's cost structure with expected market gains is a significant strategic hurdle. Fourth, the choice of business model—whether a wholesale price or marketplace structure—further complicates adoption decisions. The implications of blockchain on pricing, commissions, and profit margins differ across models, introducing complexity in evaluating its overall value. For example, under the wholesale price model, retailers may be more trusted by consumers and less reliant on blockchain for quality assurance, whereas marketplace models depend heavily on transparency to compensate for asymmetric information. Lastly, information asymmetry between manufacturers, retailers, and consumers persists in the absence of blockchain. Traditional quality inspection mechanisms are costly and prone to inefficiencies, which makes blockchain attractive—but only under the right structural and market conditions.

The authors developed a game-theoretic analytical model representing a simplified supply chain comprising a manufacturer, an online retailer, and heterogeneous consumers. The model captures strategic interactions under two dominant business structures: the wholesale price model and the marketplace model. The research begins with a benchmark scenario without blockchain, in which the retailer employs traditional quality inspections, and pricing is shaped by commission structures and quality penalties. This is contrasted with scenarios incorporating blockchain technology, where transparency replaces conventional inspection mechanisms and enhances consumer perception.



Consumers are divided into two primary groups. Quality-conscious consumers, who derive increased utility from blockchain-enabled transparency. Quality-indifferent consumers, who perceive no additional benefit from blockchain adoption. To better reflect real-world heterogeneity, an extended model includes **continuous variation in consumer perception**, treating the marginal value of blockchain as a uniform distribution within the quality-conscious segment.

The analysis incorporates two distinct retail structures.The manufacturer sells to the retailer at a fixed price, and the retailer determines the final consumer price. The retailer acts as a platform and earns a commission, while the manufacturer sets the consumer price. The model explores how blockchain alters pricing dynamics, profitability, and consumer surplus under each structure.

Blockchain's adoption is modeled by introducing:

- **Cost parameters**: Including per-unit adoption cost (s) and a quadratic cost function (kb^2) for transparency.
- **Consumer utility functions**: Integrating blockchain-driven benefits (θb) and potential **privacy costs** (h).
- **Market demand**: Calculated from the utility-maximizing behavior of each consumer group.

The study derives closed-form expressions for optimal wholesale and retail prices, profit functions for both manufacturer and retailer and total market demand under various parameter configurations. Comparative statics and propositions are presented to highlight key insights, such as the conditions under which blockchain enhances profits or leads to price increases. The analysis includes extensions to account for Consumer privacy concerns, Heterogeneous consumer preferences and Consumer surplus effects. The robustness of results is demonstrated through graphical illustrations (e.g., equilibrium zones, utility curves) and propositional logic, showing how different levels of cost, quality, and transparency shape adoption outcomes.

[3] The integration of blockchain technology into green supply chain management (GSCM) under conditions of demand uncertainty presents a unique set of challenges. While

blockchain is often celebrated for its ability to enhance transparency, traceability, and data security, its real-world implementation in eco-friendly supply chains reveals complex trade-offs.

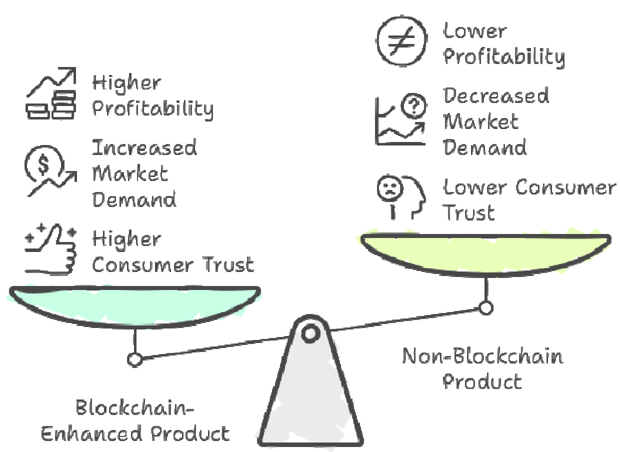
A primary challenge identified is consumer uncertainty regarding green product attributes. Despite increasing environmental awareness, consumers often doubt the authenticity of green claims due to a lack of verifiable data. This skepticism negatively impacts their willingness to pay a premium for eco-friendly products, reducing market demand and discouraging sustainable investment by manufacturers.

Moreover, demand volatility poses a substantial obstacle. Fluctuating consumer preferences, driven by shifts in environmental concerns and trust levels, create instability in pricing strategies and investment decisions. Traditional models, which assume static market conditions, fall short of capturing these real-time behavioral changes.

Another significant challenge lies in the cost of green innovation. The high R&D expenses associated with enhancing product sustainability, especially under uncertain returns, can discourage firms from adopting or maintaining green initiatives. Furthermore, while blockchain can theoretically boost consumer trust, its implementation does not guarantee better environmental performance and may in some scenarios prioritize profit maximization over sustainability. The research considers two competing manufacturers in an oligopolistic market, each producing a green product—one with blockchain-enhanced traceability and one without. Consumer utility functions are modeled to account for

- Green uncertainty (τ): Reflecting consumer doubt about environmental claims.
- Blockchain acceptance (θ): Representing the degree to which consumers value blockchain-enabled transparency.

The study defines distinct utility equations for both product types and constructs corresponding demand functions, allowing the derivation of equilibrium prices, demands, and profit functions.



Balancing Blockchain Benefits in Green Supply Chains

A two-stage non-cooperative game is employed to simulate the strategic behavior of manufacturers:

1. Stage one involves investment decisions in green R&D to enhance the environmental attributes of products.
2. Stage two focuses on pricing decisions, influenced by the competitor's previous choices.

Backward induction is used to solve the game, yielding closed-form expressions for optimal strategies under both static and dynamic conditions.

The authors construct a discrete-time dynamic system using difference equations. These capture the evolution of green R&D investments based on marginal profit changes and learning parameters (δ_1, δ_2). The system's behavior is further analyzed for:

- Equilibrium points (e.g., Nash equilibrium),
- Bifurcation and chaotic trajectories, and
- System stability using the Jury and Lyapunov criteria.

A delayed feedback control mechanism is proposed to mitigate instability and chaos, ensuring that the green supply chain system can remain resilient under market fluctuations.The model is validated through simulations using realistic parameter values drawn from prior studies (e.g., $m = 1$, $\tau = 0.2$, $\theta = 0.8$). Results are visualized using Equi-periodic maps, Bifurcation diagrams and Lyapunov exponent charts, highlighting the sensitivity of system performance to changes in investment responsiveness and consumer behavior.

[4] Despite the growing global demand for halal-certified products, the halal supply chain faces numerous challenges that hinder consistent certification and consumer trust. These challenges are both perceptual and operational, particularly across Asian countries and global supply chains with diverse stakeholders.

One of the most pressing issues is the lack of understanding and awareness regarding halal certification requirements. Many businesses, particularly small and medium-sized enterprises (SMEs), lack adequate knowledge and training to handle halal products correctly, increasing the risk of cross-contamination and procedural non-compliance. This challenge is further complicated by cultural resistance, where halal food is sometimes perceived as exclusive or foreign, reducing broader market engagement.

Another challenge is the scarcity of halal-certified ingredients in several regions, which limits manufacturers' ability to ensure full compliance across the supply chain. This shortage often leads to sourcing compromises, undermining the integrity of the final product.

The halal certification process itself is complex and resource-intensive, especially in countries where no centralized halal authority exists. Organizations are often burdened by high costs, prolonged audit procedures, and inconsistent regulatory standards, which vary across jurisdictions. The absence of harmonized guidelines leads to confusion among producers and certification bodies, especially in cross-border contexts.

Moreover, the traceability of halal products is constrained by fragmented and outdated record-keeping systems. Technical limitations in data collection, lack of digital infrastructure, and susceptibility to fraud further compromise traceability. Trust deficits among consumers and stakeholders—exacerbated by past instances of mislabeling and certification fraud—remain a significant barrier to widespread acceptance.

The first phase involved a comprehensive literature review examining existing halal certification practices, blockchain traceability applications, and the use of artificial intelligence (AI) in food supply chains. The review synthesized regulatory, technological, and managerial perspectives, identifying both knowledge gaps and opportunities for innovation. This foundational review guided the conceptualization of a holistic, technology-enabled solution.

Building on insights from the literature, the study proposes a three-layered framework for halal compliance, covering:

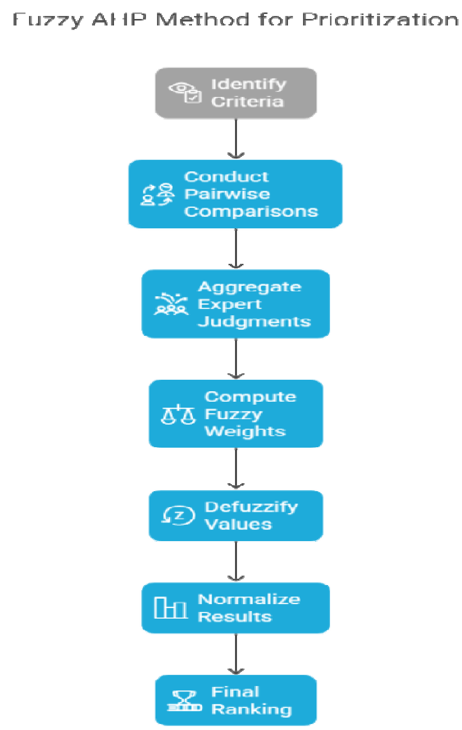
- Product Validation: Verifying ingredients against halal standards;
- Production Process Validation: Ensuring compliance in food preparation and handling;
- Logistics Validation: Maintaining integrity during transport, storage, and distribution.

The framework integrates blockchain technology as a decentralized, tamper-proof ledger for traceability and AI capabilities for intelligent decision-making. AI applications include knowledge graphs for semantic reasoning, machine learning (ML) models for classifying halal/haram food items, and smart contracts for automating compliance verification. The integration of Artificial Intelligence (AI) and Blockchain Technology in healthcare supply chains presents significant potential but also introduces multifaceted challenges that span technological, organizational, and regulatory domains.

One major challenge is the complexity and heterogeneity of healthcare data. The healthcare ecosystem involves diverse stakeholders—including hospitals, manufacturers, insurers, and patients—each generating voluminous and sensitive data. Ensuring secure, real-time, and interoperable data exchange across this fragmented network requires advanced technological infrastructure that is often absent in developing systems. Second, data privacy and security remain paramount concerns. While blockchain ensures immutable record-keeping, its public and transparent nature can conflict with the confidentiality requirements of medical data. Similarly, AI systems depend heavily on access to large datasets, raising ethical and legal questions about patient consent, data ownership, and misuse. Third, the lack of standardization and regulatory support hampers the scalability of AI-blockchain systems. Varying standards for electronic health records (EHRs), incompatible platforms, and insufficient compliance frameworks across jurisdictions inhibit seamless implementation. Fourth, technology acceptance among stakeholders is limited. Medical professionals, supply chain managers, and IT personnel often exhibit reluctance to adopt new systems due to unfamiliarity, training gaps, or resistance to change. This is further compounded by the cost of deployment, which includes investment in infrastructure, staff training, and maintenance.

Finally, the difficulty in prioritizing integration factors—such as trustworthiness, data security, clinical relevance, and real-time responsiveness—makes it challenging to develop clear implementation strategies. Without a structured approach to evaluating and ranking these factors, healthcare organizations risk suboptimal investment and adoption outcomes.

The study employs a hybrid multi-criteria decision-making (MCDM) methodology, specifically integrating Fuzzy Analytic Hierarchy Process (F-AHP) and Fuzzy Decision-Making Trial and Evaluation Laboratory (F-DEMATEL). The research began with a systematic literature review, from which four primary criteria and 23 sub-criteria were identified based on relevance to AI and blockchain adoption in healthcare contexts. These criteria were categorized under Digital Health, Smart Health, Integrated Health and Accessible Health. Each group encompasses elements like health monitoring, clinical decision support, treatment process integration, stakeholder participation, and data security. The F-AHP method was applied to prioritize the identified criteria by capturing the subjective judgments of healthcare and technology experts under uncertainty. Experts conducted pairwise comparisons using a fuzzy scale, allowing for imprecise linguistic assessments to be translated into triangular fuzzy numbers. The process involved for constructing a pairwise comparison matrix, aggregating expert judgments, computing fuzzy weights and defuzzified values and normalizing results to derive the final ranking of each criterion and sub-criterion.



This approach ensured robust prioritization by considering both expert uncertainty and the hierarchical structure of the criteria. Following the prioritization, F-DEMATEL was employed to determine the causal relationships among the sub-criteria. This technique allowed the researchers to map interdependencies, distinguishing between influencing (cause) and influenced (effect) factors. The methodology included building a direct-relation matrix using fuzzy linguistic terms, normalizing the matrix, calculating total-relation matrices and defuzzifying and plotting the cause-effect diagram. The output of this step revealed key influencing sub-criteria such as technology acceptance, stakeholder participation, and integration of treatment processes, which significantly impact other areas like patient-centered treatment and fraud detection.

[5] Small and Medium-Sized Enterprises (SMEs) are increasingly recognized as pivotal drivers of economic development and innovation, particularly in emerging economies. However, their pursuit of sustainable business performance (SBP) is significantly constrained by a number of structural, technological, and strategic challenges.

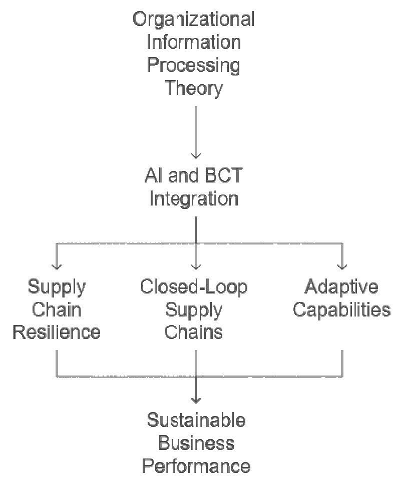
A central challenge lies in the limited digital capability and readiness of many SMEs. Unlike large corporations, SMEs often lack the necessary financial, human, and technological resources to adopt advanced technologies such as Artificial Intelligence (AI) and Blockchain Technology (BCT). This digital divide limits their capacity to leverage digital tools for improving operational resilience, sustainability, and competitiveness.

Furthermore, the adoption of closed-loop supply chain (CLSC) models is hindered by inadequate infrastructure and expertise in reverse logistics and waste recovery processes. Many SMEs struggle to manage product returns, recycling, and remanufacturing efficiently due to a lack of strategic vision and coordination across supply chain partners.

In the context of supply chain resilience (SCR), SMEs face challenges in proactively responding to disruptions caused by geopolitical uncertainties, pandemics, or raw material shortages. Despite the potential of AI to forecast and mitigate such risks, SMEs often fail to implement such tools due to organizational inertia and technological unfamiliarity. Another challenge addressed in the study is the unclear strategic value of the metaverse for SMEs. While the metaverse promises an immersive and integrated platform for digital transformation, its practical implications for supply chain management and sustainability remain underexplored and misunderstood by SME stakeholders. These interconnected challenges underscore the need for a theoretically grounded and empirically validated framework that clarifies how AI and BCT can be effectively integrated to support SCR, CLSC, and ultimately, sustainable development in SMEs.

The study adopts a quantitative, theory-driven methodology, combining Organizational Information Processing Theory (OIPT) with a structural equation modeling (SEM) approach to examine the interrelationships among key constructs related to AI and BCT integration in SME supply chains. The research is grounded in Organizational Information Processing Theory, which posits that firms facing high levels of environmental uncertainty and task complexity must enhance their information processing capabilities. The study conceptualizes Artificial Intelligence (AI) and Blockchain Technology (BCT) as information-processing mechanisms that enable SMEs to improve decision-making, coordination, and responsiveness. Under this framework, the study hypothesizes relationships among the following constructs AI and BCT capabilities, Supply Chain Resilience (SCR), Closed-Loop Supply Chains (CLSC), Adaptive Capabilities (AC) and Sustainable Business Performance (SBP). The research employed a survey-based data collection method, targeting SME managers and decision-makers involved in digital transformation and supply chain management. A structured questionnaire was developed based on validated scales from prior literature, measuring perceptions and capabilities related to AI, BCT, SCR, CLSC, AC, and SBP.

Research Methodology and Conceptual Framework



The final sample comprised 261 responses from SMEs operating in diverse sectors, ensuring coverage of firms with varying degrees of digital maturity and supply chain complexity. The collected data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) via SmartPLS software. This technique was selected for its robustness in handling complex, multivariate models and its suitability for theory development in exploratory studies. The methodology involved Assessment of measurement model validity and reliability, including composite reliability, average variance extracted (AVE), and discriminant validity. Evaluation of the structural model to test hypotheses and path coefficients. Variance explained (R^2) and predictive relevance (Q^2) to assess model fit. Examination of direct, indirect, and mediating effects, particularly the role of Adaptive Capabilities (AC) in linking technology adoption to sustainable outcomes. The SEM analysis confirmed the positive and significant effects of AI and BCT on both SCR and CLSC, which in turn influenced AC and ultimately enhanced SBP. The findings validated the proposed theoretical model and provided empirical evidence supporting the transformative potential of digital technologies in SME sustainability.

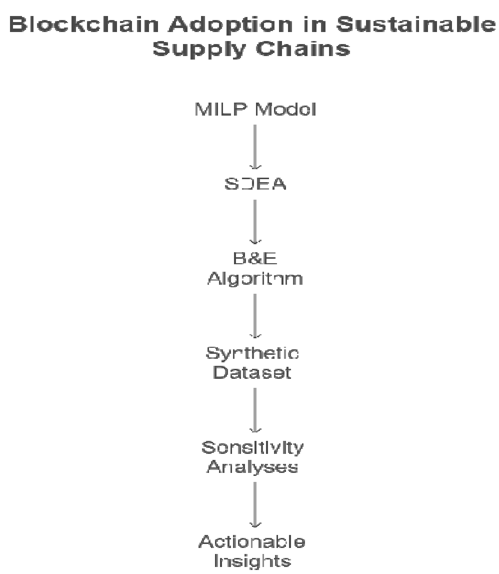
[6] While blockchain technology offers promising applications for improving transparency, traceability, and trust in supply chains, its integration into green and two-echelon supply chains presents several technical and strategic challenges. These challenges arise from the inherent complexity of multi-tiered networks, environmental considerations, and the costs associated with distributed ledger systems.

One of the primary challenges is the lack of clarity regarding the appropriate level of tracing granularity. Supply chains face the dilemma of choosing between product-level tracing (recording the entire lifecycle of products across nodes) and component-level tracing (capturing transactional data between members or transportation links). Each approach entails distinct implications in terms of data accuracy, system complexity, and implementation cost.

Secondly, the high operational cost of blockchain implementation—particularly when considering smart contract execution, data storage, and energy usage—can be prohibitive for many supply chain configurations. When integrating blockchain for green supply chains, these costs are further compounded by the need to balance environmental performance (e.g., carbon footprint) with economic feasibility.

Another significant challenge is the absence of a standard framework or mathematical model to evaluate the trade-offs between blockchain configuration complexity, transparency, and supply chain performance. Most prior studies are conceptual or qualitative in nature, lacking robust optimization tools to assess blockchain's impact on service level, cost efficiency, and supply chain design. Moreover, existing systems struggle with determining where and by whom blockchain blocks should be generated—whether by supply chain members (nodes) or by transportation links. The choice of block-generating authority influences not only traceability and trust dynamics, but also the overall blockchain architecture, complicating system-wide integration. Collectively, these challenges emphasize the need for a quantitative decision-making framework that enables comparison of multiple blockchain adoption modes under operational, financial, and sustainability constraints.

To address the above challenges, the authors propose a quantitative optimization framework that models and compares multiple blockchain adoption scenarios within a two-echelon green supply chain. The methodology integrates Mixed-Integer Linear Programming (MILP) and Simultaneous Data Envelopment Analysis (SDEA) with a customized Branch and Efficiency (B&E) algorithm to balance the trade-offs between cost, transparency, and service level. The study begins by classifying blockchain adoption into four distinct scenarios based on block-generating authorities like Product Tracing by Members, Product Tracing by Links, Component Tracing by Members and Component Tracing by Links. Each scenario is designed to reflect real-world blockchain deployment configurations. Product tracing focuses on end-to-end tracking of green products, while component tracing captures pairwise interactions among entities. These scenarios form the basis of the optimization model.



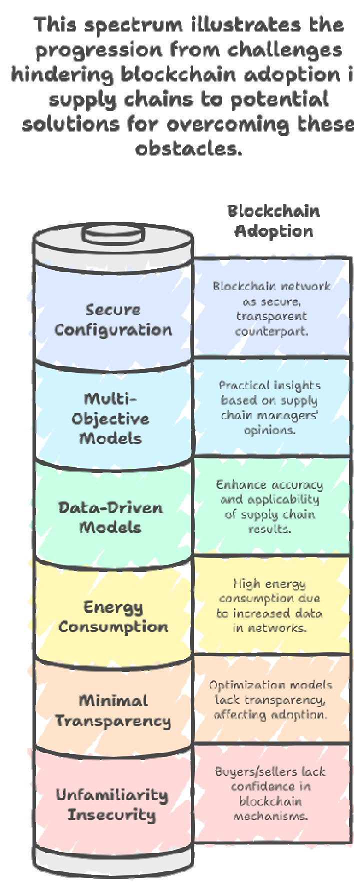
A Mixed-Integer Linear Programming (MILP) model is developed to simultaneously optimize Supply chain design and flow decisions, Blockchain block generation location and structure, Green product production and transportation. The objective function minimizes total cost, incorporating operational costs, blockchain implementation costs, and environmental impacts such as CO_2 emissions. Constraints are applied to ensure capacity limits, demand fulfillment, and logical flow of goods.

To evaluate the relative efficiency of different blockchain adoption scenarios, the study utilizes Simultaneous Data Envelopment Analysis (SDEA)—a technique that measures the performance of decision-making units (DMUs) across multiple objectives. Here, each adoption scenario is treated as a DMU, assessed based on Total cost, Transparency level (measured by the number and placement of blockchain blocks) and Service level (on-time deliveries). A novel Branch and Efficiency (B&E) algorithm is developed to integrate SDEA with the MILP solver. This hybrid technique enables the model to explore multiple supply chain configurations and to evaluate trade-offs among competing objectives and identify Pareto-optimal blockchain adoption strategies. The model is tested using a synthetic dataset simulating a two-echelon supply chain with green product flows and varying blockchain implementation costs. Sensitivity analyses are conducted to assess the effect of Blockchain cost variations, Service-level targets and Carbon footprint constraints. The results demonstrate how different tracing configurations influence efficiency, cost, and transparency, providing actionable insights for practitioners seeking to implement blockchain in sustainable supply chains.

[7] The research provides a first-of-its-kind classification for blockchain adoption in supply chain design, addressing the lack of clear frameworks in existing literature. Two perspectives (member-based and link-based) and two strategies (product racing and component tracing) are identified to classify blockchain adoption into four general cases. Novel Mixed-Integer Linear Programming (MILP) models were developed to design blockchain-enabled two-echelon supply chains.

These models were extended to address real-world cases of product traceability and component tracing based on participation in links and nodes of the supply chain. An innovative solution methodology was proposed using the Branch and Efficiency (B&E) algorithm combined with Simultaneous Data Envelopment Analysis (SDEA). This approach considers cost, service, and blockchain-related criteria to optimize supply chain design while ensuring transparency and efficiency. A benchmark example from prior literature validated the applicability of the proposed methodology. Sensitivity analyses provided deeper insights into the robustness of the models under varying conditions.The findings offer valuable decision-making aids for supply chain managers, emphasizing cost reduction, increased transparency, and iterative solutions to enhance performance. Previous studies have not provided a comprehensive classification for adopting blockchain in supply chain design, limiting access to references for this research. Due to the innovative nature of blockchain, many industries have not yet adopted it or published their data, restricting access to real-world blockchain applications in supply chains.

Increased reliance on IoT tools like QR codes and RFID for converting physical flows into digital flows leads to higher energy consumption and operational costs. Technical issues such as energy inefficiency and dependence on IoT tools remain unresolved. Buyers and sellers unfamiliar with blockchain mechanisms feel insecure, hindering widespread adoption. Minimal transparency and insufficient attention to the effects of blockchain length and associated costs in optimization models pose additional challenges. Insufficient research exists on investigating the impacts of blockchain length, minimal transparency, and adoption costs in supply chain optimization models. Future research should consider uncertain conditions in blockchain adoption to better model real-world scenarios. Developing multi-objective models based on supply chain managers' opinions can provide more practical insights. Incorporating data-driven models can further enhance the accuracy and applicability of the results. Investigating additional case studies across diverse industries will broaden the understanding of blockchain-enabled supply chains. Extending the research to supply chains with more echelons beyond the two-echelon focus of this study is recommended. Exploring the configuration of the blockchain network as a secure and transparent counterpart to traditional supply chains is a key area for future work. Addressing the issue of insecurity among supply chain participants by enhancing their familiarity and trust in blockchain mechanisms is crucial. Finding solutions to reduce energy consumption associated with increased data in blockchain networks remains an open challenge.



Customizing and implementing hybrid models that combine blockchain with other technologies (e.g., IoT, AI) could lead to more efficient supply chain designs. Collaborating with industries to validate and refine the general models presented in this research will ensure their practical relevance. Investigating the regulatory and ethical implications of blockchain adoption in supply chains can guide policymakers and practitioners. This research significantly contributes to the field of blockchain-enabled supply chain design by addressing critical gaps in the literature. It provides a foundational framework for classifying blockchain adoption, develops novel optimization models, and proposes an efficient solution approach. However, technical and non-technical challenges, along with limited data availability, highlight the need for further investigation. Future research directions emphasize the importance of addressing uncertainty, energy consumption, and security concerns while exploring new configurations and multi-echelon supply chains. By bridging these gaps, researchers and practitioners can unlock the full potential of blockchain technology in creating transparent, efficient, and sustainable supply chains.

IV. **Conclusion**

Blockchain technology holds transformative potential for supply chains across sectors, driven by the need for transparency, trust, and sustainability. However, its adoption must be carefully evaluated against operational costs, consumer preferences, and environmental objectives. Future research should focus on dynamic modeling, privacy-enhanced blockchain systems, and cross-sector standardization efforts.

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