International Journal of Engineering Trends and Technology
ISSN: 2231-5381/ https://doi.org/10.14445/22315381/IJETT-V74I3P124

Volume 74 Issue 3, 353-368, March 2026

Original Article

Enhancing Sustainability and Transparency in Food Supply Chains through Blockchain-Based Traceability, Smart Contracts, and Decentralized Data Security in E-Business Environment

Laith T. Khrais[1], Ahmad Ali Salih[2], Ahmed Mahmoud Mohamed Elnokirah[3], Lama Talal Khrais[4]

[1,2]*Faculty of Business, Middle East University, Jordan.*
[3]*Faculty of Commerce, Menofia University, Jordan,*
[4]*Faculty of Aviation Sciences, Amman Arab University, Jordan.*

[1]*Corresponding Author : Lkhrais@meu.edu.jo.*

Received: 18 August 2025 Revised: 06 November 2025 Accepted: 06 February 2026 Published: 28 March 2026

Abstract - *Currently, the pandemic of sustainability concerns is being considered along with the issues related to transparency and efficiency in the global food supply chain. Despite growing research on blockchain in food logistics, few studies integrate traceability, smart contracts, and decentralized security into a single model for enhancing sustainability and transparency. This study bridges that gap. In addition, blockchain technology is a transformational solution that facilitates stakeholders to build trust, operational efficiency, and traceability. From a management perspective, this research also examined the part that blockchain plays in the food supply chain, including its possible effect or impact on sustainability, ethical sourcing, transparency, and efficiency in the food retail chain. This study's methodology is a quantitative research approach. The method in the study was purposive sampling, while survey questionnaires were used. A total of 280 participants have participated in the study. In this research, key blockchain applications, such as traceability systems, decentralized ledgers, and smart contracts, are examined. Besides, blockchain improved the rate at which the supply chain worked through removing inefficiencies, automating transactions, and enhancing workflow efficiency. It also reinforced trust by proper and clear product traceability and compliance with the regulatory standards and ethical sourcing. The results, however, suggest that blockchain technology holds the ability to undermine the handling of the supply chain, where efficiencies in resource management and sustainable practices, fair trade, and convenient coordination are facilitated. Apart from the above, blockchain technology offers a solid and suitable platform for boosting sustainability in operational efficiencies and streamlining the food supply chain to the farthest point. But the ongoing adoption process continues to shape the future of resilient and transparent food systems.*

Keywords - *Blockchain, Ethical sourcing, Food supply chain, Supply chain efficiency, Smart contracts, Traceability, Transparency.*

1. Introduction

The universal "food supply chain" stands as a critical and multi-layered procedure involving several stakeholders, consisting of "consumers, retailers, distributors, manufacturers, and farmers." In the supply chain, traceability and sustainability are acknowledged as critical concerns due to aspects including "contamination risks, ineffective tracking procedures, and fraudulent practices" in ensuring food security. Therefore, conventional supply chain management depends on unified databases, which are vulnerable to cybersecurity threats, inadequate transparency, and data manipulation [1]. Such challenges have been found appropriate to be solved by blockchain technology by developing a transparent, immutable, and decentralized ledger system. Therefore, blockchain promotes the entire supply chain efficacy, reduces fraud, and increases traceability through the association of decentralized data security, automated processes, and smart contracts [2]. However, existing studies often focus on individual aspects such as traceability or data security, rather than a holistic integration of blockchain mechanisms within food supply systems. This leaves a methodological gap in understanding how these combined elements contribute to both sustainability and stakeholder trust. The current research addresses issues of traceability when providing and sustainability in the food supply chain that can be improved thanks to blockchain-based transparency. "Blockchain technology" provides various advantages for food supply chain management [3-5]. The benefits or advantages of blockchain involve "decentralized security, waste reduction and sustainability, improved food safety, and increased traceability." Secondly, blockchain lowers the chances of data manipulation and data breach as it stands as a tamper-proof ledger unlike as in the traditional centralized ones. Additionally, blockchain leverages sustainable agricultural practices and reduces food wastage by enhancing efficacy in "logistics and inventory management." Consequently, blockchain makes possible decisions and the withdrawal of the products that have been affected, thus limiting potential health risk related to recalls or contamination. Blockchain allows food products to be monitored as they travel from farm to table in real time in order to ensure quality control and authenticity.

However, here are some challenges faced in the food supply chain industry, with the adoption of Blockchain as the main part of the argument. (technological inclusion, regulative incorporation, and scalability). Researchers have confirmed that Blockchain is in the right place when it comes to the field of food supply chain management. Therefore, the result shows that the blockchain-based traceability process implemented in a supply chain increases efficiency, which leads to the trust of consumers. For example, Walmart and IBM's food trust initiative leverages blockchain to track food products until they are produced, and products that did this successfully reduced the time to trace back damaged products massively [6].

The literature criticizes that blockchain incorporation is still in the early stages, with issues about high adoption expense and interoperability between energy consumption and supply chain procedures in blockchain networks [7]. Researchers also argue whether decentralized networks can change traditional regulatory models without effective legal support [8]. The main goal of this study is to find out how blockchain based transparency contributes to transforming the food supply chains by looking at the effect of the main blockchain components, including Blockchain Based Traceability (BBT), Smart Contract Implementation (SCI), Decentralized Data Security (DDS), and Stakeholder Trust and Adoption (STA) on the emergence of Sustainable and Transparent Food Supply Chain (STFSC). Furthermore, the mediating effect of Supply Chain Efficiency (SCE), in that such blockchain-based involvements enhance the relationship between increased FSC transparency and sustainability, is also studied. This study is novel in integrating four blockchain-driven factors (traceability, smart contracts, decentralized security, and stakeholder trust) into a unified model to evaluate their collective effect on building a sustainable and transparent food supply chain. Therefore, to address this research aim, four research objectives are as follows:

- "To analyze the effect of BBT, SCI, DDS, and STA on the development of an STFSC". "To understand the mediating role of SCE in the association between blockchain-based factors and an STFSC".
- "To ascertain the major prospects and challenges associated with incorporating blockchain technology in the food supply chain process".
- "To establish a predictive model measuring the robustness of blockchain-based strategies in promoting 'supply chain sustainability, efficiency, and transparency' in the food industry."

Specifically, the research addresses the following hypotheses:

H1: "Blockchain-Based Traceability (BBT) positively influences the development of a Sustainable and Transparent Food Supply Chain (STFSC)".

H2: "Smart Contract Implementation (SCI) positively influences the development of a Sustainable and Transparent Food Supply Chain (STFSC)".

H3: "Decentralized Data Security (DDS) positively influences the development of a Sustainable and Transparent Food Supply Chain (STFSC)".

H4: "Stakeholder Trust and Adoption (STA) positively influence the development of a Sustainable and Transparent Food Supply Chain (STFSC)".

H5: "There is a mediating effect of Supply Chain Efficiency (SCE) towards the development of a Sustainable and Transparent Food Supply Chain (STFSC)".

Moreover, the study's significance depends on its competency to facilitate a structured model for blockchain incorporation in food supply chains, confirming efficiency, security, safety, and traceability while stimulating industry-based regulatory compliance and trust. Therefore, this research facilitates actionable perspectives for supply chain stakeholders, industry leaders, and policymakers seeking to promote sustainability, clarity, and food security through applying cutting-edge blockchain.

The research investigates the way blockchain-based transparency, through "stakeholder trust, decentralized data security, smart contracts, and traceability, improves traceability and sustainability" in "food supply chain management". However, the outcomes emphasize that supply chain competency possesses a mediating role, reinforcing the effect of blockchain incorporation on consistency and clarity. In addition, the study helps confirm the effect of blockchain in supply chains and supports different theories by confirming that supply chain efficiency and trust of stakeholders are core components. Alongside this, this research offers strategic guidelines for assisting policymakers, industry adoption, supply chain regulators, and managers in supporting blockchain for operational potential, fraud mitigation, and food safety. Further investigations are needed to investigate long-term blockchain implementation impacts, regional changes, and the association of the “Internet of Things (IoT)” and “Artificial Intelligence (AI)” to improve supply chain sustainability and transparency again.

2. Materials and Methods

2.1. Materials

2.1.1. Theoretical Perspectives

In practice, blockchain is an immutable and decentralized ledger that offers the capability for several stakeholders in the food supply chain field to understand and check transaction data [9]. Distributed Ledger Technology (DLT) decreases fraud, improves traceability, and removes information asymmetry, making it an essential innovation for food sustainability and safety[10].

Transaction Cost Theory (TCT) demonstrates how organizations seek to reduce expenses through the integration of enforcement, supervision, and transactions [11]. Blockchain, especially smart contracts, decreases such expenses by restructuring compliance, removing intermediaries, and automating trust-driven transactions [12]. Researchers reported that supply chains can practice high contractual transparency and cost efficiency by supporting blockchain.

The “Resource-Based View” (RBV) indicates that organizations with inimitable, rare, and valuable resources acquire a competitive edge [13]. Blockchain improves supply chain operational efficiency, security, and resilience, which can be a strategic resource for organizations implementing such technology [14]. Organizations spending on blockchain establish transparent and sustainable supply chain networks, resulting in long-term competitiveness and improved brand trust.

Rogers's “Innovation Diffusion Theory” (IDT) demonstrates how emerging technologies are incorporated throughout industries [15]. At the same time, blockchain implementation in food supply chains relies on comparative advantage, adaptability, observability, trialability, compatibility, and difficulty [16]. Previous adopters in the food sectors like Nestlé and Walmart have illustrated the practical advantages of blockchain-driven traceability, stimulating wider incorporation [17]. In summary, the theoretical perspectives reviewed, Transaction Cost Theory (TCT), Resource-Based View (RBV), and Innovation Diffusion Theory (IDT) collectively frame how blockchain artifacts (smart contracts, immutable ledgers, and decentralized security) can become strategic resources that reduce transaction costs, enable competitive advantage, and diffuse across food supply organizations. These theories, therefore, provide the conceptual basis for the model tested in this study: TCT explains how SCI and DDS may reduce enforcement and monitoring costs (affecting SCE), RBV supports the idea that BBT and DDS can become firm-level resources that improve STFSC, and IDT explains variability in STA across stakeholder groups. By explicitly linking each theory to the study variables (BBT, SCI, DDS, STA, SCE, STFSC), this section justifies our hypothesized relationships and the use of SEM to test them.

2.1.2. Food Supply Chain and Blockchain Transparency

The worldwide “food supply chain” sector has also been an integration of digitalisation, and as a matter of fact, it has transformed what customers' lifestyles are into something different. Ensuring the safety and security of the end consumer is ensured through robust monitoring of food items within the supply chain system. The food supply chain sector is currently not well placed to outline the food items since there is no clarity and visibility in tracking the movement, process, transportation, distribution, and production of the food through the supply chain, which poses a challenge to the consumers’ safety as well as the quality of the processed items.

The literature presented an IoT-driven and blockchain-based model to operate and monitor the working of the processed poultry industry of the food supply chain. This also optimized the distribution by the efficiency of the quality and safety of the food items, which were directed as end consumables. Hence, the objective intent is to determine the forms of corruption and debasement that can be associated with foods, to bring out clarity to the transactions and legal liability, and ultimately will contribute to the safety and quality of food supply in the food industry, and will ultimately have a high positive impact on the whole brand value and consumer trust [18].

The internationalization of the supply chain makes its administration and supervision more complex. However, “blockchain technology” as a shared digital ledger system that proves security, traceability, and transparency, is an indication that it is dedicated to fixing some of those global supply chain management problems. The researcher reported that smart contracts and blockchain technology seem to be essentially analyzed with competent implementation to supply chain administration.

Consumers, the community, and international and domestic governments are forced to address sustainability objectives quickly, and people need to explore again how blockchain can cover and assist sustainability in the supply chain. Partially, the complex investigation tends to focus on how blockchain, a competent disruptive process that is prior in its changes, leads to recovery of several possible challenges. Alongside this, four different blockchain technology implementation challenges were presented, such as external, technical, intra-organizational, and inter-organizational challenges. The continuation of the development process for actual blockchain-driven transformations of supply chain and business is followed by the researcher's remarks, suggesting further research directions and recommendations that can assist with resolving and incorporating the blockchain system for supply chain administration [19].

Collectively, these studies establish blockchain's potential to improve traceability and end-to-end visibility in food supply chains, but they also highlight practical constraints (interoperability, cost, and governance). For the current model, the literature supports BBT as a direct antecedent of STFSC (through improved product provenance and recall capability) and as an enabler of SCE (through faster information flows).

2.1.3. Automation and Smart Contracts in the Food Supply Chain

The challenges of a supply chain process make quality concerns and product safety problems highly complex to track, particularly for the fundamental cultivated food supply chain management of people's regular nourishment. The currently cultivated food supply chains introduced diverse key issues, including several respondents, problematic interactions that occurred over long cycles of the supply chain, and data suspicion between the centralized system and the respondents. The development of the blockchain procedure actively cracks the pain-point issue presenting in the cultivated food supply chains' traceability system.

The researcher offered a model dependent on the smart contracts and the associations to follow and monitor the cultivated food supply chains' workflow, adopt distribution and traceability of supply chains, and classify the data keys between organizations to reduce the requirement for the dominant agencies and organizations and optimize the association of the transaction security, reliability, and records. However, there are certain faults; the model successfully observed practices, including tracing and disintermediation of cultivated product evidence via QR codes. Moreover, the model offered in this research possesses large relevance and opportunity for organizations to confirm product safety and quality traceability [20].

The scenario was looking at building traceability systems as real-time techniques to enhance the traceability and visual engagement of a supply chain in case of safety and health-related sectors, such as economic products, food, and pharmaceuticals. Therefore, blockchain-based supply chain traceability studies obtained substantial importance during the past few decades, and it is debatable whether blockchain is considered in providing traceability-based services in supply chain networks; it provides highly competent technology. The researcher did an SLR ("systematic literature review") of several technical features of the blockchain-enabled supply chain traceability procedures. Academic practitioners concentrated on the unorganized analysis of blockchain-integrated supply chain traceability remedies despite the substantial surfeit and range of blockchain-based supply chain traceability processes, and a transparent requirement was there for designing and examining practical traceability remedies, particularly considering cost-based and feasibility supply chain factors [21].

These studies collectively highlight the potential of smart contracts in improving traceability, automating compliance checks, and reducing administrative overhead in supply chains. However, much of the extant literature is conceptual or limited to technical prototypes; few studies provide robust quantitative evidence on how SCI affects both SCE and STFSC in operational settings. In our model, SCI is therefore posited as both a direct driver of STFSC (by automating provenance and compliance) and an indirect driver via SCE (by improving transactional speed and reducing errors).

2.1.4. Risk Mitigation and Decentralized Data Security

In the present situation, the internationalization of the "food supply chain" sector has substantially developed. For this reason, farm-to-fork food quality and safety documentation is considered an essential factor. Growing challenges to food corruption and safety resulted in massive requirements for an innovative traceability process, an essential instrument for particular quality control that confirms adequate food supply chain items' security. This study offered a blockchain-driven remedy that eliminates the requirement for a safe centralized framework, intermediaries, or connections of data, improves performance, and is associated with an effective degree of integrity and security.

The method in this case only depends on the utilization of smart agreements to follow and keep track of all the relations and dealings among the supply chain channels as they happen among all the investors. This particular method checked all the dealings, which were documented and embraced in a unified interplanetary database. This research permitted cost-cutting and safe supply chain procedures for the stakeholders. Moreover, the researcher recommended framework facilitates a traceable, appropriate, authentic, and clear supply chain procedure. Finally, the recommended model revealed an output of an estimated 161 dealings per second with a merging time of approximately 4.82s and was reported robust in the cultivated items' traceability [22].

This Research is based on the theory of sensemaking to study the changes being introduced by "blockchain technology" in supply chain systems. The researcher explores three research questions to address the research aim. This study employed 14 supply chain experts to develop in-depth interviews. Using narrative analysis and cognitive mapping as the primary tools of data analysis was selected to support the assessment of the research and demonstration of the cognitive difficulty of people in understanding blockchain technology. The researcher reported that different experts designed diverse cognitive frameworks within their understanding procedure. Thus, such a sensemaking method was applied under conditions of a deeper assessment of how authorities with experience identify indicators of data from blockchains, the skills, expectations, and observations about the technology that allow for the creation of initiatives in this area in the future. Finally, the researcher illustrated the application of sensemaking theory as a substitute insight in exploring modern supply chain spectacles such as blockchain [23]. The literature reviewed indicates that Decentralized Data Security (DDS) reduces single-point failures and can strengthen data integrity and auditability across food supply networks. From the perspective of our model, DDS is therefore expected to have both a direct positive effect on STFSC (through trustworthy records) and an indirect effect via SCE (by lowering the time and cost associated with verification and dispute resolution). Despite these theoretical promises, empirical measures quantifying DDS's contribution to efficiency and sustainability remain sparse and an empirical void.

2.1.5. Stakeholder Trust and Adoption of Blockchain Solutions

"Blockchain technology" is raising a lot of questions of accessibility, integrity, and confidentiality for safe and fast delivery systems of the agri-food industry supply chain. The blockchain technology is being incorporated in the agri–food supply chain of developing countries like India, which is new and underdeveloped. The research aims to investigate the operators of the incorporation of blockchain technology, in addition to the effect that those have on the behavioural intention to incorporate blockchain amongst the several stakeholders engaged in different fields of the agri-food supply chain management. From further research, a model was developed to encourage the assessment of blockchain in the agri-food supply chain and the instigation of stakeholders to explore blockchain solutions [24].

If the technology is to be operationalized, then, necessarily, significant stakeholders will have to acquire the assumed benefits. As per the incomplete contract theory, the stakeholders' actions impact the worth of an asset. However, in order to increase their applicability and satisfaction, they also must have control over the assets. However, though this technology increases trust or belief among several stakeholders in the food supply chain, their behaviour was treated individually towards whether they would include the emerging technology or not. Therefore, the research relied on the stakeholder management method that the principal organization was practicing. Moreover, organizations following the guidelines of instrumental stakeholder management are going to illustrate effective financial performance [25]. The researcher analyzed blockchain's influences on reinforcing cybersecurity and safeguarding privacy. The majority of the evidence was formally maintained in cloud information centers, and this research also differentiated blockchain practices vis-à-vis the particular cloud in several aspects of privacy and security. Major fundamental instruments compared to the effect of blockchain on the IoT ("Internet of Things") safety were also addressed.

Applying real-world illustrations and practical implementations, this research criticized that the decentralized characteristics of blockchain were possibly affecting a low vulnerability to control and imitation by spiteful respondents [26]. Existing empirical studies underscore the importance of stakeholder perceptions and behavioral intentions for technology diffusion, yet results are mixed on whether perceived benefits translate into measurable operational gains. In our conceptualization, STA is treated as both a potential direct influence on STFSC (through adoption leading to better compliance and reporting) and as a determinant of the strength of other blockchain mechanisms (e.g., higher STA may amplify the effect of SCI on SCE). Because earlier work has often measured trust qualitatively, this study contributes by testing STA quantitatively alongside technological constructs to determine its relative influence.

2.1.6. Supply Chain Efficiency

According to the WHO ("World Health Organization"), ten percent of the total population was affected by consuming polluted food. The food supply chain has started becoming gentler with the help of critical systems of food production and internationalization. Certain tools were explored in the current decades to address food uncertainty and gain knowledge in commerce with food memories. Because blockchain is characterized by features such as smart agreements, immutability, security, and decentralization, it is expected to enhance sustainable management of the food supply chain and food traceability.

The researcher found four advantages of blockchain. It leads to maximizing recall efficiency, data clarity, and food traceability, and is also associated with IoT ("Internet of Things") to gain robust potential. The researcher offered five essential barriers or challenges, such as inadequate assessment of blockchain, lack of regulations, complexities of acquiring all the investors on board, raw data control, and technology complexities [27].

Current technologies, primarily integrated with Industry 4.0, imitate substantial interruptions and require the supply chain management segment to establish emerging trade strategy frameworks. The research reported blockchain as the most competent technology. Therefore, blockchain technology initially focused on the Bitcoin field. This technology is a shared data model dependent on peer-to-peer channel dealings. Moreover, blocks were associated with cryptographic confusions, and all respective nodes possess a copy. Finally, the transaction documents were acknowledged as virtually absolute because of these characteristics [28].

The body of literature indicates that blockchain features such as smart contracts and immutable ledgers can reduce administrative delays, improve inventory turnover, and enable more accurate forecasting-all components of Supply Chain Efficiency (SCE). In our hypothesized framework, SCE is positioned as a mediator that translates technological capabilities (BBT, SCI, DDS) into sustainability outcomes (STFSC). This framing responds directly to prior calls for studies that link operational metrics (efficiency) to broader sustainability and transparency outcomes in blockchain-enabled supply chains.

2.1.7. Sustainable and Transparent Food Supply Chain

In worldwide supply chains, social sustainability seems to be a key issue for safeguarding labor from abuse and facilitating a secure working culture. However, certain specified standards regulate supply chain social consistency, and it is common to hear of organizations being informed of denial concerns. Reputable organizations like Unilever were accused of abusing the production workforce. In the current scenario, consumers highly anticipated sellers revealing data on social consistency, and sellers were faced with the barriers of traceability in respective layered worldwide supply chains. But blockchain is also a good future to enable quick traceability in the social consistency of the supply chain. Using the research, a system framework was conceptualized to associate the application of big data analytics, IoT, and blockchain to robustly and proactively monitor a seller's supply chain social conformity. Finally, possible challenges and system application expenses were evaluated before the study was developed [29].

On the contrary, traceability was obtained as the competency to trace and track data. Implementing traceability led to clarity in supply chains. Traditionally accessible, unified traceability remedies were not superior for supply chain management as they disclosed several issues, such as single failure points and data control. Therefore, blockchain is considered the currently developed shared ledger technology and is gaining fame with its strong implementations in several segments, especially in supply chain management. Alongside this, blockchain-driven traceability remedies lead to control of the limitations of unified traceability solutions. Organizations were initiated in adopting blockchain into their respective supply chain practices to optimize clarity via tracing and tracking the events [30].

Abolishing trust-associated problems means that it cuts out the supply chain network by using blockchain technology. Global research has been done on blockchain technology to support the advantages and enhance the supply chain performance. The researcher has analysed the blockchain technology and how it has numerous advantages, which have brought improvements in the consistent performance of the ASC. ("agriculture supply chain"). Food safety needs to be met in developing countries such as India, as they have a growing population that is faced by different barriers to ASC consistency. In addition, blockchain technology must also be incorporated into the ASC so that it enables many benefits. In this research, moreover, the literature settles and creates the association between the driver of the inclusion of blockchain technology in the agriculture supply chain [17]. Prior work demonstrates that sustainability and transparency gains require not only technological solutions but also governance, process redesign, and stakeholder alignment. Within the present model, STFSC represents the multidimensional outcome - environmental (reduced waste), social (ethical sourcing), and transparency (traceability). By testing multiple blockchain constructs together, this study contributes an integrated, empirically validated model showing which blockchain features most strongly drive STFSC and through what mechanisms (directly or via SCE). While the reviewed literature collectively affirms the theoretical benefits of blockchain for traceability, automation, and security in food supply chains, few studies provide an integrated quantitative assessment of multiple blockchain constructs and their combined influence on operational efficiency and sustainability. To address this gap, the following section describes a quantitative empirical strategy (sampling, measurement, and SEM-based analysis) designed to test how BBT, SCI, DDS, and STA influence STFSC directly and indirectly via SCE.

2.2. Methods

The method section reflects the research design, the data collection procedure, the sampling procedure, and the data analysis procedure in the research. Quantitative design of this study is given in this section. For the statistical test, SPSS is used to test the relationship between the incorporation aspects of blockchain technology and the establishment of a "sustainable and transparent food supply chain" SFTSC).

2.2.1. Research Design

The present study employed a quantitative study design to analyse the association between STA ("Stakeholder Trust and Adoption"), DDS ("Decentralized Data Security"), SCI ("Smart Contracts Implementation"), and BBT ("Blockchain-based Traceability") on STFSC, with a mediating variable of SCE ("Supply Chain Efficiency"). Following this, a cross-sectional survey method was used to get statistical data from the experts and professionals in the food supply chain sector. (such as retailers, distributors, manufacturers, and suppliers).

2.2.2. Population and Sampling

Supply chain regulatory officers, IT specialists, logistics managers, and professionals who are actively and directly involved in the food traceability process or the incorporation of blockchain in the equatorial belt of the country were all included in the study population. Participants were drawn from Middle Eastern and Asian regions where blockchain-based food supply initiatives are emerging, ensuring geographical diversity. The sample size of 280 was determined to be adequate based on Hair et al.'s (2019) recommendations for Structural Equation Modeling (SEM), which require a minimum of 200 responses to ensure model stability and statistical reliability. A purposive sampling technique was applied by the researcher to confirm that contributors possess significant skills and knowledge. The survey was conducted among 280 participants to confirm the statistical relevance.

2.2.3. Data Collection Procedure

The data was gathered through a structured survey questionnaire. The survey questionnaire was developed based on the validated "five-point Likert scale measurement" of 1= strongly disagree to 5= strongly agree. Therefore, the survey was shared through online platforms such as Google Forms and email invitations [31].

The elements of survey instruments involved demographic information (such as blockchain adoption level, job role, industry experience), Stakeholder Trust and Adoption (STA) [26], Decentralized Data Security (DDS) [23], Smart Contracts Implementation (SCI) [21], and Blockchain-Based Traceability (BBT) [19], Supply Chain Efficiency (SCE) [28], and Sustainable and Transparent Food Supply Chain (STFSC) [17].

2.2.4. Data Analysis Techniques

In this study, SmartPLS and SPSS were used to analyse the evidence obtained. Data cleaning and normality tests were conducted before statistical analysis to eliminate any form of incomplete or inconsistent responses. The values of skewness and kurtosis were analyzed to verify that the data met the normality assumption that is needed with multivariate analysis. The frequency distribution, SD, and means were summarized for the entire data set. During the validity and reliability study, EFA (exploratory factor analysis) was used to test the measurement items, and Cronbach's Alpha (a value of more than 0.7) was used to test the internal consistency.

Pearson's correlation was used for the correlation analysis to measure the direction and strength of association between independent variables and the dependent variable. Multiple linear regression was performed at the same time to further study the direct impacts of STA, DDS, SCI, and BBT on STFSC. Alongside this, mediation analysis was developed to understand the impact of SCE by applying Baron & Kenny's (1986) method and PROCESS macro in SPSS [32]. Additionally, SEM ("Structural Equation Modeling") was employed using SmartPLS. In this research, path analysis, model explanatory power, and bootstrapping were ascertained in the model fit. Moreover, SEM was applied for path analysis to ensure the associations between variables.

2.2.5. Ethical Considerations

In this research, the researcher followed the academic ethical guidelines involving data anonymity, informed consent, and IRB ("Institutional Review Board") approvals. All the respondents were informed about the voluntary features of the research, confidentiality, and the research purpose. In order to protect the privacy and confidentiality of the participants, the researcher did not collect any personal identifiers. The ethical research protocols were followed in the research [33].

In addition, this section highlighted the study method used to sense the influence of blockchain on the transparency and sustainability of the food supply chain. A quantitative method applying SEM and SPSS confirmed the effective statistical significance of the offered hypotheses. Therefore, the outcomes participated in both industry best practices and academic research for blockchain incorporation in the field of food supply chains.

3. Results

3.1. Introduction

Moreover, the food supply chains are more sustainable and transparent due to the smart contracts, the decentralized data security, and the blockchain provides tracing that improves the food supply chain. Besides, this study examined the effect of these technologies on Sustainable and Transparent Food Supply Chains (STFSC) and Supply Chain Efficiency (SCE). Importantly, hypothesis, validity, and reliability testing were used to test major variables. In addition, the findings provided worthwhile information regarding how the blockchain can enhance stakeholder trust and operational efficiency in the process of examining space that requires additional research.

3.2. Outer Measurement Model

Also, this study saw the relevance of Stakeholder Trust and Adoption (STA), Smart Contracts Implementation (SCI), Decentralized Data Security (DDS), and Blockchain-Based Traceability (BBT) to the achievement of a Sustainable and Transparent Food Supply Chain (STFSC) and supply chain efficiency (SCE). In addition, the outer loadings implied high construct reliability as all the factor loadings were higher than 0.7. Otherwise, the range of the "collinearity statistics (VIF) 1.754-3.830 represents the absence of issues of multicollinearity. Subsequently, the highest outer loadings of 0.897 for SCI4 and 0.910 for BBT4 suggested the strength of these indicators.

Simultaneously, SCE4 (0.880) and DDS3 (0.896) presented strong reliability. However, this study highlighted the way blockchain increased efficiency and transparency by allowing real-time tracking and immutable data recording. In addition, smart contracts automate transactions and compliance, while decentralized security mitigates fraud risks. Therefore, the findings lend some empirical support for enabling blockchain in food supply chains to promote trust and sustainability between stakeholders.

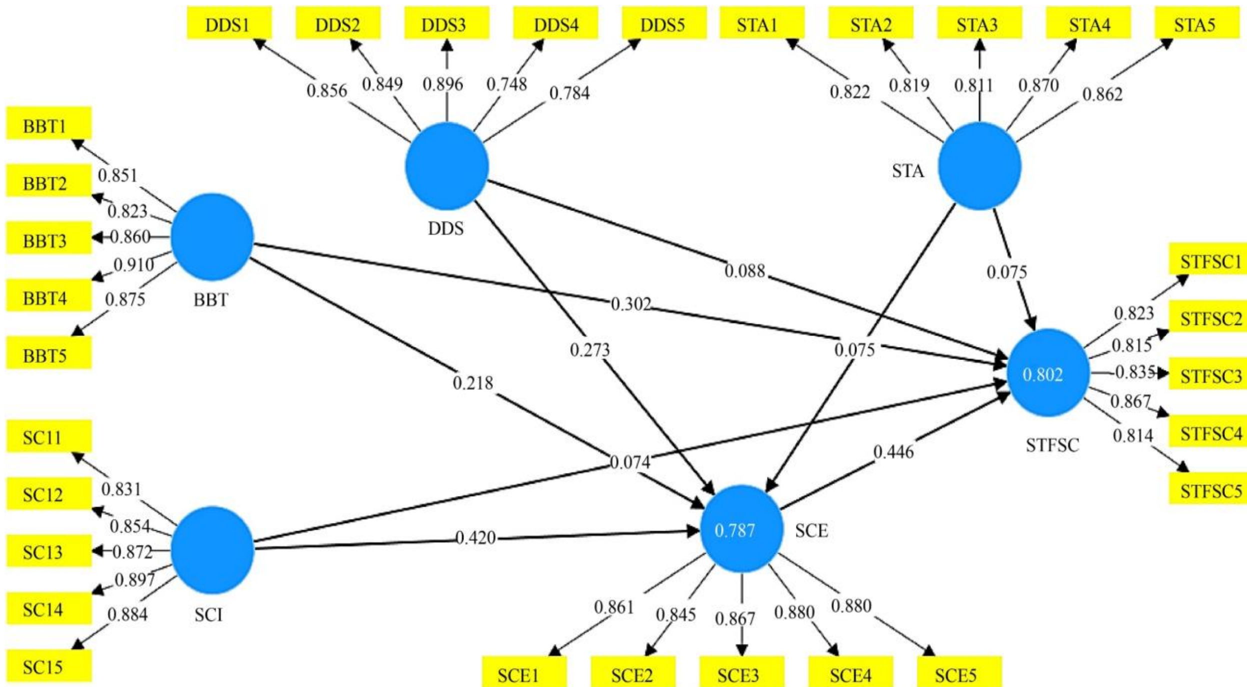

Fig. 1 Outer measurement model

Table 1. Outer loadings

	Blockchain-Based Traceability (BBT)	Decentralized Data Security (DDS)	Supply Chain Efficiency (SCE)	Smart Contracts Implementation (SCI)	Stakeholder Trust and Adoption (STA)	Sustainable and Transparent Food Supply Chain	Collinearity Statistics (VIF)
BBT1	0.851						2.427
BBT2	0.823						2.222
BBT3	0.860						2.156
BBT4	0.910						2.926
BBT5	0.875						2.750
DDS1		0.856					2.593
DDS2		0.849					2.553
DDS3		0.896					3.109
DDS4		0.748					1.790
DDS5		0.784					1.754
SCE1			0.861				2.544
SCE2			0.845				2.439
SCE3			0.867				2.731
SCE4			0.880				3.005
SCE5			0.880				2.898
SCI1				0.831			2.374
SCI2				0.854			2.652
SCI3				0.872			2.834
SCI4				0.897			3.387
SCI5				0.884			3.141

STA1					0.822		2.924
STA2					0.819		2.255
STA3					0.811		2.967
STA4					0.870		3.830
STA5					0.862		3.141
STFSC1						0.823	2.323
STFSC2						0.815	2.120
STFSC3						0.835	2.445
STFSC4						0.867	2.700
STFSC5						0.814	2.079

Table 2. Construct reliability and Average Variance Extracted (AVE)

Constructs	Cronbach's alpha	Composite reliability	Average variance extracted (AVE)
BBT	0.915	0.937	0.747
DDS	0.885	0.916	0.686
SCE	0.917	0.938	0.751
SCI	0.918	0.938	0.753
STA	0.894	0.921	0.701
STFSC	0.888	0.918	0.691

This table evaluated the validity and reliability of six key variables: BBT, DDS, SCE, SCI, STA, and STFSC. Moreover, all sections of the Cronbach's alpha scores were above 0.7, which were in the range of 0.885 to 0.888, reflecting the high internal consistency as well. Moreover, the composite reliability for the values begins at 0.916 - 0.938 and hence commences in the strong construct reliability. Furthermore, the values of AVE, potentially measuring convergent validity, were all above 0.5, confirming that the variables explained a notable portion of the variance in their indicators. Subsequently, SCI and SCE demonstrated the highest values of AVE (0.753 and 0.751, respectively), indicating strong explanatory power.

Moreover, these results further confirm that blockchain-based systems have the ability to bring robustness by enhanced efficiency, transparency, and sustainability in the food supply chain, thereby increasing their potential in building stakeholders' trust.

All constructs achieved Cronbach's Alpha values above 0.7, confirming strong internal consistency among measurement items. Composite reliability values between 0.916 and 0.938 indicate robust construct reliability, while AVE values above 0.5 confirm convergent validity. This demonstrates that the questionnaire effectively measured the underlying constructs related to blockchain traceability, smart contracts, and data security in food supply chains.

Table 3. Discriminant validity: farnell-larcker criterion

Constructs	BBT	DDS	SCE	SCI	STA	STFSC
BBT	0.864					
DDS	0.649	0.828				
SCE	0.752	0.776	0.867			
SCI	0.731	0.748	0.846	0.868		
STA	0.670	0.634	0.744	0.833	0.837	
STFSC	0.799	0.733	0.859	0.800	0.726	0.831

On the same note, the correlation matrix revealed the relationships between BBT, DDS, SCE, SCI, STA, and STFSC. Suggested also was the square root of the AVE in diagonal values, with all above with the value of 0.7, which is a high level of discriminant validity. Moreover, there exist high correlations concerning SCE and SCI (0.846) and STFSC and SCE (0.859) regarding the importance of the smart contracts and efficiency of the supply chain to sustainability. At the same time, the STFSC and BBT (0.799) accentuated the importance of traceability as a way to enhance transparency. In the meantime, construct-to-construct correlations were also significant, all of which are not higher than the square root of their respective AVE. Ensuring discriminant validity, though these findings suggest that blockchain solutions present an opportunity to develop more sustainable, efficient, and trusted food supply chains, and support the necessity of smart contracts and decentralized security in establishing trust and transparency among the stakeholders, they still increase the need to identify more efficient solutions to the issue.

3.3. Inner Structural Model

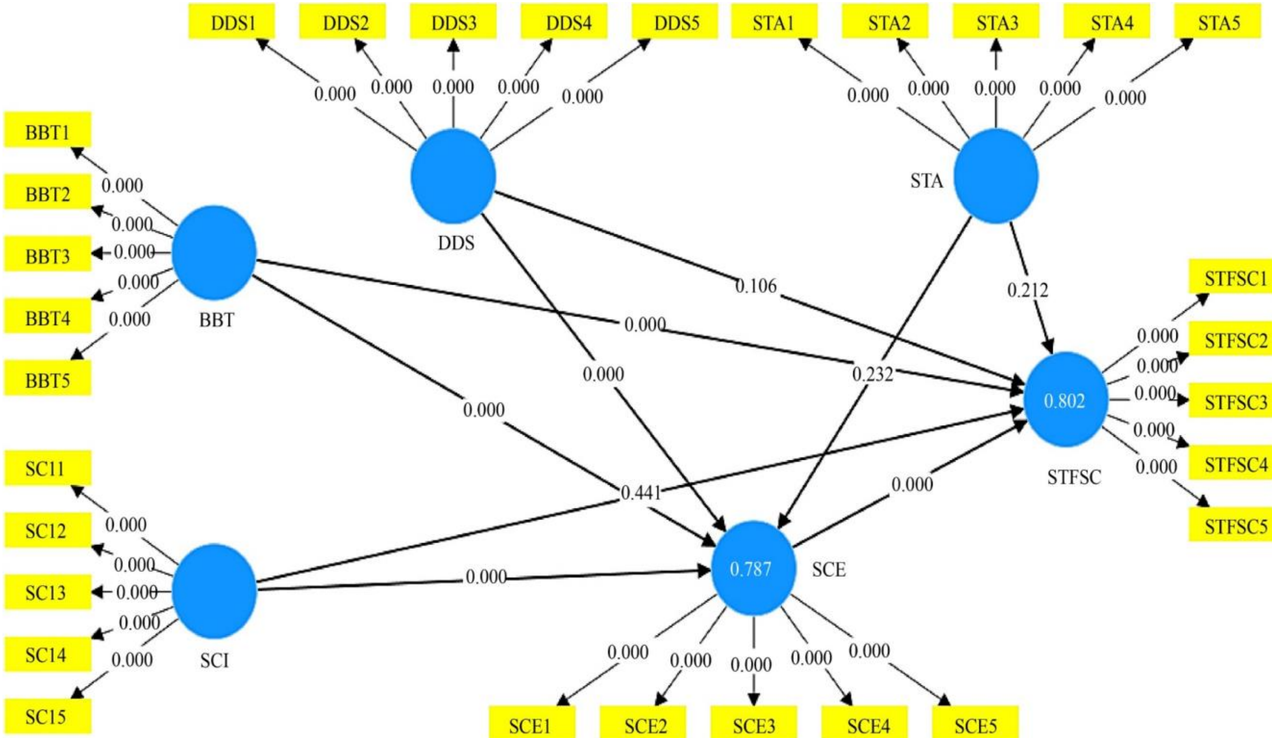

Fig. 2 Inner structural model

Table 4. Hypotheses testing

Hypotheses	Std. Beta	Std. Error	t-statistic	P values	95% CI LL	95% CI UL	Inference
BBT -> SCE	0.218	0.060	3.658**	0.000	0.123	0.317	Supported
BBT -> STFSC	0.399	0.064	6.217**	0.000	0.290	0.501	Supported
DDS -> SCE	0.273	0.063	4.302**	0.000	0.162	0.374	Supported
DDS -> STFSC	0.209	0.064	3.259**	0.001	0.104	0.314	Supported
SCE -> STFSC	0.446	0.083	5.369**	0.000	0.303	0.576	Supported
SCI -> SCE	0.420	0.075	5.571**	0.000	0.292	0.541	Supported
SCI -> STFSC	0.261	0.098	2.662**	0.008	0.102	0.424	Supported
STA -> SCE	0.075	0.063	1.196	0.232	-0.026	0.181	Not Supported
STA -> STFSC	0.108	0.070	1.553	0.121	-0.006	0.225	Not Supported
BBT -> SCE -> STFSC	0.097	0.033	2.904**	0.004	0.047	0.157	Supported
DDS -> SCE -> STFSC	0.122	0.035	3.510**	0.000	0.064	0.179	Supported
SCI -> SCE -> STFSC	0.187	0.051	3.681**	0.000	0.108	0.274	Supported
STA -> SCE -> STFSC	0.034	0.028	1.191	0.234	-0.012	0.080	Not Supported

***Significant at 0.01 level*

Importantly, the hypothesis testing outcomes provide evidence that SCI, DDS, and BBT play a major role in STFSC and SCE. Specifically, BBT has a positive impact on STFSC ($p = 0.000$, $\beta = 0.399$) and SCE ($p = 0.000$, $8 = 0.218$) and, therefore, has an impact to enhance transparency. In the same manner, STFSC ($p = 0.001$, 0.209) and SCE ($p = 0.000$, 0.273) were remarkably affected by DDS. In addition to them, SCI showed significant effects in STFSC ($p = 0.008$, 0.261) and SCE ($p = 0.000$, 0.420). Besides, there was no significant impact of STA on STFSC and SCE. This was followed by the confirmation of the mediating effect of SCT, DDS, and BBT on STFSC via SCE using the mediation analysis. Thus, the results of the study were concerned with the importance of blockchain technologies in enhancing supply chain efficiency and sustainability and implied a weak direct effect on stakeholder trust. The results show that the concepts of Traceability (BBT), the Smart Contract Implementation (SCI), and the Decentralized Data Security (DDS) play a significant role in improving the Supply Chain Efficiency (SCE) and the creation of Sustainable and Transparent Food Supply Chain (STFSC). It means that the most important technological factors in enhancing the transparency and sustainability outcomes are automation, data integrity, and traceability, and that Stakeholder Trust and Adoption (STA) needs additional reinforcement strategies.

Table 5. R-square and adjusted R-square

	R-square	R-square adjusted
SCE	0.787	0.784
STFSC	0.802	0.798

The R-square scores also indicated that 80.2% of the variance of STFSC and 78.7% of the variance of SCE were explained by the model. The adjusted R-square does imply the robustness and a strong predictive accuracy of the model; however, the values of the adjusted R-square (0.784 and 0.798) were found to be satisfactory.

Table 6. Effect size (f-square)

Hypotheses	f-square
BBT -> SCE	0.096
BBT -> STFSC	0.181
DDS -> SCE	0.146
DDS -> STFSC	0.014
SCE -> STFSC	0.213
SCI -> SCE	0.172
SCI -> STFSC	0.005
STA -> SCE	0.008
STA -> STFSC	0.008

In addition, the f-square scores highlighted each predictor's effect size on STFSC and SCE. Subsequently, BBT has a small effect on SCE (0.096) and a medium effect on STFSC (0.181). Similarly, DDS has a weak impact on STFSC (0.014) and a medium effect on SCE (0.146). However, SCI demonstrated a negligible influence on STFSC (0.005) and a medium impact on SCE (0.172). Subsequently, STA highlighted weak impacts on both STFSC (0.008) and SCE (0.008), suggesting minimal direct impact.

3.4. Summary

In summation, the findings section revealed that SCI, DDS, and BBT remarkably improved STFSC and SCE. Apart from that, as an important mediator, SCE plays a significant role in strengthening the effects of these technologies.

Moreover, STA demonstrated minimal direct influence. The strong R-squares reinforce the predictive power of the model. These insights serve as proof of the potential of blockchain in enhancing the supply chain's sustainability and as a need for the appropriate stakeholder management practices. Overall, these statistical results validate the proposed conceptual model's robustness and align with recent empirical evidence (Ellahi et al., 2023; Kaur et al., 2022), highlighting the transformative role of blockchain in improving traceability and efficiency within agri-food supply chains.

4. Discussion

4.1. Introduction

The discovery of this study is relevant as it shows the potential that blockchain technology can play in sustaining a better, more effective, and more transparent food supply chain management. Also, the supply chain stakeholders have reformed the way they communicate using blockchain-run solutions such as smart contracts, decentralized security, and traceability, ensuring flawless coordination and accountability. Nevertheless, this chapter investigated blockchain adoption's broader implications in food supply chains, focusing on its role in promoting long-term sustainability, ensuring ethical sourcing and trust, and strengthening operational efficiency. Moreover, this discussion also emphasized the way blockchain empowers organizations to meet changing customer needs while maintaining a competitive advantage in the global and local markets.

4.2. Enhancing Supply Chain Efficiency and Coordination

Further, blockchain technology significantly enhanced the effectiveness of the supply chain with its capacity to raise real-time coordination, decreasing inefficiencies, and reducing the complexity among stakeholders. Furthermore, with blockchain-powered traceability, companies can track food products at every step, from organization to table, confirming timely deliveries and accurate inventory management [34]. However, this increased visibility allowed firms to optimize the workflows of the supply chain. Improving overall productivity and eliminating unnecessary delays. Apart from that, the application of smart contracts further improved operational efficiency by reducing administrative overhead, automating transactions, and confirming that contractual agreements were performed seamlessly [35].

So, these self-executing contracts allowed real-time verification of compliance, expediting supply chain processes and eliminating intermediaries. Consequently, food retailers, manufacturers, and suppliers benefit from quick transactions, increased responsiveness to market demands, and improved resource utilization. Besides these, blockchain technology increased collaboration and communication across the network of supply chain [36]. All stakeholders have access to the same data in real-time by offering an immutable and shared ledger, promoting a more coordinated approach and reducing discrepancies in supply chain management. Subsequently, this transparency confirmed smooth operations as well as established trust among partners, strengthening the role of blockchain as a key promoter of supply chain quality and excellence. These findings are consistent with Ellahi et al. (2023), who found that blockchain-driven coordination models reduced administrative delays and enhanced responsiveness by up to 30%. Similarly, Aslam et al. (2023) confirmed that decentralized ledgers streamline logistics operations and minimize data redundancy, supporting our findings that blockchain substantially improves supply chain efficiency.

4.3. Strengthening Trust and Ethical Sourcing

Yet, among other advantages of blockchain technology in food supply chains, it is able to bring about ethical sourcing and be useful in trust promotion. Today, food transparency is expected from the customer about the origin and quality, and blockchain provides the mechanism that tests the authenticity of the purchased product [37]. Blockchain confirms to both the producer and the consumer that the food product meets safety and quality standards, end-to-end, giving the consumer confidence in their purchases of the product. Significantly, this technology also has a notable role in supporting ethical sourcing initiatives and fair trade.

Simultaneously, companies used blockchain to verify whether suppliers obeyed regulatory compliance, sustainable farming methods, and ethical labor practices [38]. Additionally, blockchain, by offering verifiable proof of production and sourcing processes, empowered customers to make informed decisions while encouraging firms to maintain ethical standards. Subsequently, blockchain strengthened the protocols of food safety by allowing accurate and swift product recalls. Nevertheless, in contamination-related issues, firms can isolate and identify affected batches practically, reducing risks to customers and preventing extensive disruptions [39].

Lastly, this proactive approach increased the trust of the customer and reinforced the food supply chains' credibility. These insights correspond with Kshetri (2021) and Lin et al. (2021), who demonstrated that blockchain-based traceability enhances consumer confidence through transparent supply chain information. Our results extend these conclusions by quantitatively validating that trust and ethical sourcing are strengthened when traceability and smart contracts function together.

4.4. Driving Sustainability and Long-Term Growth

Blockchain technology was a key driver in food supply chains because it provided firms with the opportunity to use environmentally friendly practices without sacrificing profitability and efficiency [40]. However, blockchain, by offering accurate data on resource utilization, assisted firms in minimizing their carbon footprint, reducing waste, and optimizing production. Furthermore, one of the notable facets of blockchain's contribution towards sustainability was its capability of preventing unnecessary waste and tracking food expiration dates [41]. Additionally, retailers used blockchain data to incorporate dynamic strategies of pricing, providing discounts on goods approaching their dates of expiration, thereby maximizing revenue and reducing food wastage. Moreover, blockchain allows more precise demand forecasting, enabling firms to adjust distribution and production accordingly, further reducing excess stock [42].

Whereas sustainable sourcing is another important area, and in this area, blockchain technology has a considerable role. Blockchain, by offering transparency into sourcing practices, confirmed that the supply chain of food prioritized environment-friendly practices following suppliers [43]. So, this incentivized water conservation, reduced pesticide use, and the adoption of sustainable farming methods, contributing to the overall health of the world. Apart from that, companies that incorporate blockchain-driven sustainability initiatives achieve a competitive edge in the competitive market [44]. Blockchain offers a tangible way for firms to demonstrate their sustainability efforts, increasing customer loyalty and brand reputation as customers increasingly favor brands committed to environmental responsibility.

4.5. Summary

Lastly, blockchain technology is changing the food supply chains by making them more sustainable, building trust, and enhancing efficiency. Moreover, the capability of food products for food applications actually ensured the smooth coordination of the supply chain and proper management of inventory, which enhanced responsiveness and minimized inefficiency. Ethical sourcing and trust. Smart contracts and blockchain-based traceability enhanced accountability and transparency by providing verifiable evidence of compliance with suppliers and product integrity.

Notably, sustainability programs facilitated by blockchain helped businesses contribute to the sustainability of sourcing related to the environment, managing resource use, and minimizing waste. With the ongoing development of blockchain adoption, the food supply chain is becoming more resilient, efficient, and transparent, which proves the success and growth of the supply chain over the long term and in an ever-increasing competitive environment.

4.6. Challenges and Limitations

In spite of these obvious advantages, there are a number of technological and organizational obstacles to blockchain usage in the food supply chain. The deployment is usually limited by scalability, integration with existing legacy systems, and the high cost of implementation in small and medium enterprises. Furthermore, the lack of comprehensive legal regulations and interoperability criteria poses ambiguity to international buys and sells. The impact of organizational resistance to digital transformation and lack of technical knowledge on the supply chain actors is also a hindrance to widespread adoption. The inhibitors to leveraging the potential of blockchain in the sustainable food supply network will have to be combated by means of government incentives, training, and standardized procedures.

5. Conclusion

The research paper empirically confirms the fact that the use of blockchain elements contributes to sustainability and transparency in food supply chains. The research presents evidence of the ability of blockchain to enhance operational and environmental performance by incorporating traceability, smart contracts, and decentralized data security into a single model. In conclusion, the food supply chain processing with the help of blockchain technology can transform the currently existing process into a more stable, transparent, and efficient one. Businesses can coordinate with frictionless communication and have the ability to eliminate inefficiencies and coordinate processes through the advancements in smart contracts, real-time coordination, and blockchain-based traceability. Nevertheless, all these developments are incredibly productive in general and reduce delays and improve inventory optimization. Later, blockchain enhanced accountability and trust through providing verifiable evidence of ethical sourcing, compliance of suppliers, and authenticity of the products. Besides, the customers increasingly require the transparency of the food production process, and the blockchain technology ensures compliance with fair-trade, safety, and quality standards. Blockchain, by promoting sustainable framing opportunities and responsible labor practices, promoted responsible business practices and consumer confidence.

Moreover, sustainability also plays a positive role in the implementation of blockchain because it will help companies reduce their impact on the environment and food waste, and manage resources to maximize their use. Blockchain, through environmentally friendly sourcing, improved demand forecasting, and monitoring food expiration dates, has helped in long-term sustainability and maximizing profitability. Moreover, it has experienced a definite role in technology in transforming the food supply chains that will eventually lead to more sustainable, reliable, and efficient food supply chains.

Nevertheless, with the adoption of blockchain, the competitive market will gain advantages, innovation will happen, and businesses will be in a position to respond to the shifting demands of consumers in favor of the responsible and resilient food system on a global level. By integrating these blockchain mechanisms, this model contributes a practical framework for future technology-driven food governance and offers a benchmark for researchers and policymakers seeking to implement data-secure, transparent, and sustainable supply chain systems.

5.1. Recommendations

In order to implement blockchain technology for improving benefits in the food supply chain management, stakeholders, businesses, and policymakers need to take proactive steps to confirm the long-term success and smooth integration. First, companies need to invest in blockchain training programs and infrastructure to optimize operational efficiency and increase adoption [45]. Furthermore, stakeholders need to be educated on the potential of technology and best practices to confirm effective incorporation. Subsequently, companies need to collaborate with technology providers to develop user-friendly blockchain solutions customized to their particular needs of the supply chain. Apart from the above, there is a need to clearly set regulatory frameworks that allow the use of blockchain, yet that conform to industry standards, interoperability, and data security [46]. However, standardized protocols will enable seamless communication among the partners of the supply chain and increase overall transparency.

In addition, businesses need to use blockchain for sustainability practices by implementing real-time monitoring, reducing food waste, and prioritizing ethical sourcing for better utilization of resources [47]. In addition, the smart contracts may also be used to validate fair trade activities and guarantee sustainability pledges. Moreover, the necessity of the partnership of research facilities, government structures, and industrial players in the industry in the promotion of blockchain innovation is highlighted. Importantly, the pilot projects and collaboration will encourage companies to perfect and experiment with blockchain applications and ensure the success and scalability over the long term [48].

Food supply chains via such recommendations, therefore, can reap the full benefits of blockchain, achieving greater sustainability, trust, and efficiency, and remain competitive in an expanding and evolving market. Pilot blockchain deployments in the logistics networks, cold-chain, and export documentation can also be used as real-world testbeds to test the scalability and cost-effectiveness. Regulatory authorities and industry associations would support such pilot programs and show the concrete advantages of blockchain and inform bigger policy frameworks to adopt a meaningful usage.

5.2. Limitations of the Study

Although this study provides much information that can be used to understand the application of blockchain in the process of food supply management, it is limited in some aspects. The first problem has to do with the fact that the study was a quantitative study that relied on a survey, and the findings were based on self-reported information, which might have been misinterpreted by the respondents or was biased [48].

Also, the accuracy of responses is dependent on the experience and familiarity of the people involved in the blockchain technology, and this may compromise the reliability of the results. In addition to them, the geographic coverage and sample size of this study are limited, which might limit the generalizability of the findings to a larger population. The acceptance of blockchain and its impact on supply chains, as a rule, may be different among companies of various sizes, industries, and regions, and require additional research and comparison. Also, blockchain technology is rapidly transforming, and new innovations are affecting its performance and implementation in supply chains [48, 49]. Moreover, the outcomes of the research were dependent on the existing developments that might have evolved with time. Findings on the final position entail difficulties of change resistance amongst the stakeholders, uncertainties regarding the regulations, and high implementation costs that are not researched in-depth. Therefore, these aspects would be added to the future research to offer a comprehensive picture of blockchain usefulness in food supply chains on a daily basis. [50, 51].

5.3. Future Perspectives

Regarding food supply chain management, however, the future of blockchain is extremely promising because of its sustainability, potential for efficiency, and innovation. Moreover, as technology keeps undergoing changes, one can further promote its compatibility with IoT and AI, change its capacity to automate decision-making, predictive analytics, and tracking in real time. As an example, the further development of these will then enable a proactive approach with regard to the supply chain that will, in turn, improve resource allocation and also reduce wastage. There will also be regulatory changes that will affect how blockchain will be used in food supply chains. Governments and industry organizations put in place policies that required the traceability and transparency that helped to speed up the adoption of blockchain in world markets. Moreover, future studies must explore the regulatory environment and how it affects the use of blockchain. Besides, as consumers and businesses are getting more conscious about sustainability and sourcing in an ethical manner, blockchain can play a critical role in ensuring that environmental regulations and fair trade are adhered to. Finally, the research efforts must also focus on how the sustainability efforts supported by blockchain technology affect business strategies and consumer behavior. Overall. Blockchain is developed in a manner that it can transform food supply chains and make them more resilient, efficient, and transparent.

References

[1] Maria Teresa Gaudio, Sudip Chakraborty, and Stefano Curcio, "Agri-Food Supply-Chain Traceability: A Multi-Layered Solution," *2022 IEEE International Conference on Dependable, Autonomic and Secure Computing, International Conference on Pervasive Intelligence and Computing, International Conference on Cloud and Big Data Computing, International Conference on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech)*, Falerna, Italy, pp. 1-5, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[2] Mohammad Ikbal Hossain et al., "Enhancing Data Integrity and Traceability in Industry Cyber Physical Systems (ICPS) through Blockchain Technology: A Comprehensive Approach," *arXiv preprint*, pp. 1-17, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Amanpreet Kaur et al., "Adaptation of IoT with Blockchain in Food Supply Chain Management: An Analysis-based Review in Development, Benefits and Potential Applications," *Sensors*, vol. 22, no. 21, pp. 1-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Panagiota Katsikoul et al., "On the Benefits and Challenges of Blockchains for Managing Food Supply Chains," *Journal of the Science of Food and Agriculture*, vol. 101, no. 6, pp. 2175-2181, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[5] Showkat Ahmad Bhat et al., "Agriculture-Food Supply Chain Management based on Blockchain and IoT: A Narrative on Enterprise Blockchain Interoperability," *Agriculture*, vol. 12, no. 1, pp. 1-25, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[6] Alba J. Collart, and Elizabeth Canales, "How Might Broad Adoption of Blockchain-based Traceability Impact the U.S. Fresh Produce Supply Chain?," *Applied Economics Perspectives and Policy*, vol. 44, no. 1, pp. 219-236, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[7] Behzad Esmaeilian et al., "Blockchain for the Future of Sustainable Supply Chain Management in Industry 4.0," *Resources, Conservation and Recycling*, vol. 163, pp. 1-16, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Andrej Zwitter, and Jilles Hazenberg, "Decentralized Network Governance: Blockchain Technology and the Future of Regulation," *Frontiers in Blockchain*, vol. 3, pp. 1-12, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] Petri Helo, and Ahm Shamsuzzoha, "Real-Time Supply Chain-A Blockchain Architecture for Project Deliveries," *Robotics and Computer-Integrated Manufacturing*, vol. 63, pp. 1-26, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[10] Jamilya Nurgazina et al., "Distributed Ledger Technology Applications in Food Supply Chains: A Review of Challenges and Future Research Directions," *Sustainability*, vol. 13, no. 8, pp. 1-26, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] Abdikadir Noor Fidow, Selefano Odoyo, and Francis Wambalaba, "The Effect of Transaction Cost on the Performance of SMEs in Kenya," *International Journal of Accounting, Finance and Risk Management*, vol. 7, no. 1, pp. 11-19, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Elena Isabel Vazquez Melendez, Paul Bergey, and Brett Smith, "Blockchain Technology for Supply Chain Provenance: Increasing Supply Chain Efficiency and Consumer Trust," *Supply Chain Management: An International Journal*, vol. 29, no. 4, pp. 706-730, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[13] Elisabeth Baia, João J. Ferreira, and Ricardo Rodrigues, "Value and Rareness of Resources and Capabilities as Sources of Competitive Advantage and Superior Performance," *Knowledge Management Research and Practice*, vol. 18, no. 3, pp. 249-262, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[14] Javed Aslam, Aqeela Saleem, and Yun Bae Kim, "Blockchain-Enabled Supply Chain Management: Integrated Impact on Firm Performance and Robustness Capabilities," *Business Process Management Journal*, vol. 29, no. 6, pp. 1680-1705, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Ronald J. Salazar et al., "Diffusion of Innovative Technology in US Oil and Gas Industry: An Empirical Study," *International Journal of Technology, Policy and Management*, vol. 20, no. 1, pp. 1-20, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[16] Mohd Helmi Ali et al., "Investigating Blockchain Technology Adoption Intention Model in Halal Food Small and Medium Enterprises: Moderating Role of Supply Chain Integration," *International Journal of Logistics Research and Applications*, vol. 27, no. 12, pp. 2753-2777, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[17] Sachin S. Kamble, Angappa Gunasekaran, and Rohit Sharma, "Modeling the Blockchain Enabled Traceability in Agriculture Supply Chain," *International Journal of Information Management*, vol. 52, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[18] Munir Majdalawieh et al., "Blockchain-based Solution for Secure and Transparent Food Supply Chain Network," *Peer-to-Peer Networking and Applications*, vol. 14, no. 6, pp. 3831-3850, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Sara Saberi et al., "Blockchain Technology and its Relationships to Sustainable Supply Chain Management," *International Journal of Production Research*, vol. 57, no. 7, pp. 2117-2135, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[20] Lu Wang et al., "Smart Contract-based Agricultural Food Supply Chain Traceability," *IEEE access*, vol. 9, pp. 9296-9307, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[21] Thomas K. Dasaklis et al., "A Systematic Literature Review of Blockchain-Enabled Supply Chain Traceability Implementations," *Sustainability*, vol. 14, no. 4, pp. 1-30, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[22] Deepak Prashar et al., "Blockchain-based Traceability and Visibility for Agricultural Products: A Decentralized Way of Ensuring Food Safety in India," *Sustainability*, vol. 12, no. 8, pp. 1-20, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[23] Yingli Wang et al., "Making Sense of Blockchain Technology: How Will it Transform Supply Chains?," *International Journal of Production Economics*, vol. 211, pp. 221-236, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] Anandika Sharma et al., "Blockchain Adoption in Agri-Food Supply Chain Management: An Empirical Study of the Main Drivers using Extended UTAUT," *Business Process Management Journal*, vol. 29, no. 3, pp. 737-756, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[25] Michael Paul Kramer, Linda Bitsch, and Jon H. Hanf, "The Impact of Instrumental Stakeholder Management on Blockchain Technology Adoption Behavior in Agri-Food Supply Chains," *Journal of Risk and Financial Management*, vol. 14, no. 12, pp. 1-20, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[26] Nir Kshetri, "Blockchain's Roles in Strengthening Cybersecurity and Protecting Privacy," *Telecommunications Policy*, vol. 41, no. 10, pp. 1027-1038, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[27] Jiang Duan et al., "A Content-Analysis based Literature Review in Blockchain Adoption within Food Supply Chain," *International Journal of Environmental Research and Public Health*, vol. 17, no. 5, pp. 1-17, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[28] Maciel M. Queiroz, Renato Telles, and Silvia H. Bonilla, "Blockchain and Supply Chain Management Integration: A Systematic Review of the Literature," *Supply Chain Management: An International Journal*, vol. 25, no. 2, pp. 241-254, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[29] V.G. Venkatesh et al., "System Architecture for Blockchain based Transparency of Supply Chain Social Sustainability," *Robotics and Computer-Integrated Manufacturing*, vol. 63, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[30] Justin Sunny, Naveen Undralla, and V. Madhusudanan Pillai, "Supply Chain Transparency through Blockchain-based Traceability: An Overview with Demonstration," *Computers and Industrial Engineering*, vol. 150, pp. 1-52, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[31] Anahita Ghanad, "An Overview of Quantitative Research Methods," *International Journal of Multidisciplinary Research and Analysis*, vol. 6, no. 8, pp. 3794-3803, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[32] Mary Appah et al., "Comparison of Methods for Mediation Analysis with Multiple Correlated Mediators," *arXiv preprint*, pp. 1-47, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[33] Alistair McBeath, *Doing Quantitative Research with a Survey*, Enjoying Research in Counselling and Psychotherapy, Palgrave Macmillan, Cham, pp. 175-193, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[34] Rizwan Matloob Ellahi, Lincoln C. Wood, and Alaa El-Din Ahmed Bekhit, "Blockchain-based Frameworks for Food Traceability: A Systematic Review," *Foods*, vol. 12, no. 16, pp. 1-28, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[35] Shuchih Ernest Chang, Yi-Chian Chen, and Ming-Fang Lu, "Supply Chain Re-Engineering using Blockchain Technology: A Case of Smart Contract based Tracking Process," *Technological Forecasting and Social Change*, vol. 144, pp. 1-11, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[36] Abderahman Rejeb et al., "Potentials of Blockchain Technologies for Supply Chain Collaboration: A Conceptual Framework," *The International Journal of Logistics Management*, vol. 32, no. 3, pp. 973-994, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[37] Xin Lin et al., "Consumers' Intention to Adopt Blockchain Food Traceability Technology Towards Organic Food Products," *International Journal of Environmental Research and Public Health*, vol. 18, no. 3, pp. 1-19, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[38] Nir Kshetri, "Blockchain and Sustainable Supply Chain Management in Developing Countries," *International Journal of Information Management*, vol. 60, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[39] V. Sri Vigna Hema, and Annamalai Manickavasagan, "Blockchain Implementation for Food Safety in Supply Chain: A Review," *Comprehensive Reviews in Food Science Food Safety*, vol. 23, no. 5, pp. 1-29, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[40] Nicola Friedman, and Jarrod Ormiston, "Blockchain as a Sustainability-Oriented Innovation?: Opportunities for and Resistance to Blockchain Technology as a Driver of Sustainability in Global Food Supply Chains," *Technological Forecasting and Social Change*, vol. 175, pp. 1-17, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[41] A. Chandan, M. John, and V. Potdar, "Achieving UN SDGs in Food Supply Chain using Blockchain Technology," *Sustainability*, vol. 15, no. 3, pp. 1-21, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[42] Vinolyn Vijaykumar et al., *Convergence of IoT, Artificial Intelligence and Blockchain Approaches for Supply Chain Management*, Blockchain, IoT, and AI Technologies for Supply Chain Management, Apress, Berkeley, CA, pp. 45-89, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[43] Shoufeng Cao, Henry Xu, and Kim P. Bryceson, "Blockchain Traceability for Sustainability Communication in Food Supply Chains: An Architectural Framework, Design Pathway and Considerations," *Sustainability*, vol. 15, no. 18, pp. 1-21, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[44] Nusi Drljevic, Daniel Arias Aranda, and Vladimir Stantchev, "An Integrated Adoption Model to Manage Blockchain-Driven Business Innovation in a Sustainable Way," *Sustainability*, vol. 14, no. 5, pp. 1-21, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[45] Mohammad Raihanul Hasan et al., "Operational Efficiency Effects of Blockchain Technology Implementation in Firms: Evidence from China," *Review of International Business and Strategy*, vol. 30, no. 2, pp. 163-181, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[46] Ghulam Mustafa et al., "Blockchain-based Governance Models in E-Government: A Comprehensive Framework for Legal, Technical, Ethical and Security Considerations," *International Journal of Law and Management*, vol. 67, no. 1, pp. 37-55, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[47] Megha Chauhan, and Deepali Rani Sahoo, "Towards A Greener Tomorrow: Exploring the Potential of AI, Blockchain, and IoT in Sustainable Development," *Nature Environment and Pollution Technology*, vol. 23, no. 2, pp. 1105-1113, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[48] Anniina Saari et al., "Best Practices for Blockchain-Driven Digital Transformation in Traditional Industries," *SSRN*, pp. 1-22, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[49] Hoda M. Aboalsamh, Laith T. Khrais, and Sami A. Albahussain, "Pioneering Perception of Green Fintech in Promoting Sustainable Digital Services Application within Smart Cities," *Sustainability*, vol. 15, no. 14, pp. 1-13, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[50] Ibrahim A. Abu-AlSondos, "Eliminating Data Silos with Business Intelligence: The Role of Organizational Culture and Leadership in Jordan's Insurance Sector," *Insurance Markets and Companies*, vol. 16. no. 2, pp. 24-37, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[51] Ahmad Ali Atieh Ali et al., The Role of Digital Supply Chain on Inventory Management Effectiveness within Engineering Companies in Jordan, Sustainability, vol. 16, no. 18, pp. 1-25, 2024. [CrossRef] [Google Scholar] [Publisher Link]