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Research Article

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

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Abstract:

Currently, being considered is the pandemic of sustainability concerns along with the issues related to transparency and efficiency in the global food supply chain. In addition, blockchain technology is a transformational solution that facilitates stakeholders to build trust, operational efficiency and traceability. From 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 as well as efficiency in food retail chain. This study's methodology is quantitative research approach. The method in the study was a purposive sampling while survey questionnaires were used. A total of 280 participants have participated in the study. In this research, it was explored key blockchain applications as such as traceability systems, decentralized ledgers and smart contracts. Besides, blockchain improved the rate at which the supply chain worked through removing the inefficiencies, automating transactions and enhancing the 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 suitable platform for boosting sustainability in operational efficiencies and streaming the food supply chain to the farthest point. But the adoption of this unnatural process continued and ultimately shaped the future of resilient and transparent food systems.

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 close 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]. 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] [4] [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 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, there are some advantages of Blockchain which include transparency and traceability, however, here are some challenges faced in food supply chain industry 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 the food supply chain management. Therefore, the result shows that the blockchain based traceability process implemented in a supply chain increases efficiency that leads to the trust of consumers. For example, Walmart and IBM's food trust initiative leverages blockchain to watch food products until they are produced and products that did this successfully reduced the time to trace back down 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 BBT ("Blockchain Based Traceability"), SCI ("Smart Contract Implementation"), DDS ("Decentralized Data Security"), and STA ("Stakeholder Trust and Adoption") on the emergence of STFSC ("Sustainable and Transparent Food Supply Chain"). Furthermore, the mediating effect of SCE ("Supply Chain Efficiency"), in that such blockchain based involvements enhance the relationship between an increased FSC transparency and sustainability, is also studied. 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 integrated 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 stakeholder are core components. Alongside this, especially, 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 of several stakeholders in 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 Nestle and Walmart, have illustrated the practical advantages of blockchain-driven traceability, stimulating wider incorporation[17].

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 safety and security of end consumer is ensured through robust monitoring of food items within the supply chain system. 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 process of 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 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 foods supply in the food industry and will ultimately have 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 essentially analysed with competent implementation to supply chain administration. Consumers, the community, and international and domestic governments are forced to address sustainability objectives quickly, and people to again explore 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 incorporation of the blockchain system for supply chain administration[19].

2.1.3 Automation and Smart Contracts in 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 nourishments. The currently cultivated food supply chains introduced diverse key issues, including several respondents, problematic interactions that occurred by 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 decline the requirement for the dominant agencies and organizations and optimize the association of the transaction security, reliability, and records. However, still, 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 economical products, food and pharmaceuticals. Therefore, blockchain-based supply chain traceability studies obtained substantial importance during the past few decades, and debatably 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 the 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].

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 associates with an effective degree of integrity and security. The method in this case only depends on 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 in each 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].

2.1.5 Stakeholder Trust and Adoption of Blockchain Solutions

“Block chain technology” is blocking a lot of questions of accessibility, integrity, confidentiality for safe and fast delivery systems of agri-food industry supply chain. The blockchain technology is being incorporated in the Agri–food supply chain of developing countries like India is new and underdeveloped. The research aims to investigate the operators of the incorporation of blockchain technology also 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 the further research, there was a model 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’s 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 on 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 such a 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 ways 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].

2.1.6 Supply Chain Efficiency

According to WHO (“World Health Organization”), ten percent of the total population was affected by consuming polluted food. The food supply chain has started becoming gentle 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 what it is characterized as, with features such as smart agreements, immutability, security and decentralization, it has been expected to enhance sustainable management of 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 also be 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 impose 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 such characteristics[28].

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 argued for 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 itself 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 acquiring 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 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 the blockchain technology. Global research has been done for blockchain technology to support advantages and enhance the supply chain performance. The researcher has analysed the blockchain technology and how it has numerous advantages which have brought the improvements of 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 in the ASC so it enables the 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].

2.2 Methods

The method section reflects into 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 among the incorporation aspects of blockchain technology and the establishment ("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 through the experts and professionals during 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 incorporation of blockchain in the equatorial belt of the country were all included in the study population. A purposive sampling technique was used 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), STA ("Stakeholder Trust and Adoption")[26], DDS

("Decentralized Data Security")[23], SCI ("Smart Contracts Implementation")[21], and BBT ("Blockchain-based Traceability")[19], SCE ("Supply Chain Efficiency")[28], and STFSC ("sustainable and transparent food supply chain")[17].

2.2.4 Data Analysis Techniques

In this research, the collected evidence was analyzed using SmartPLS and SPSS. The descriptive statistics summarized the frequency distribution, standard deviation, and mean for the whole dataset. In the validity and reliability analysis, EFA ("exploratory factor analysis") validated the measurement items, and Cronbach's Alpha (with a value of >0.7) examined the internal consistency. Pearson's correlation was used for the correlation analysis to measure the direction and strength of association between independent variables and 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 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 and reported about the voluntary features of research, confidentiality, and 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 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

In addition, the smart contracts, decentralized data security, and the blockchain based tracing which enhance food supply chain make the food supply chains more sustainable and transparent. Moreover, this research investigated the influence of these technologies on sustainable and transparent food supply chains (STFSC) and supply chain efficiency (SCE). Significantly, key variables were assessed using hypothesis, validity, and reliability testing. Moreover, the findings offered valuable knowledge about the blockchain's role in improving stakeholder trust and operational efficiency while exploring areas that need further investigation.

3.2 Outer Measurement Model

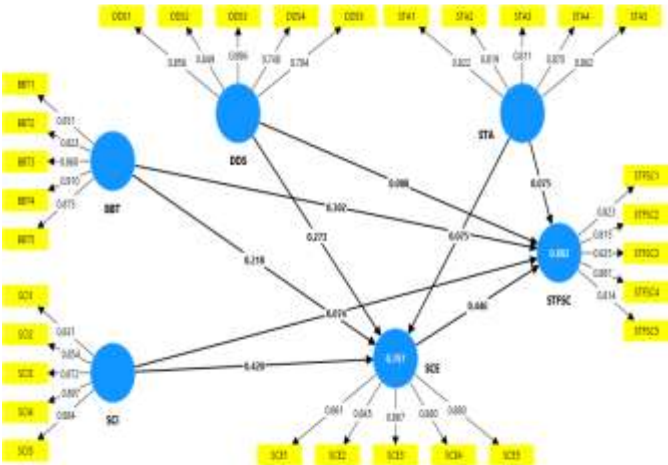

Figure 1. *Outer Measurement Model*

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 (STFSC)	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
STFSC						0.823	2.323
STFSC						0.815	2.120
STFSC						0.835	2.445
STFSC						0.867	2.700
STFSC						0.814	2.079

Additionally, this research examined the importance of “stakeholder trust and adoption (STA)”, “smart contracts implementation (SCI)”, “decentralized data security (DDS)” and “blockchain-based traceability (BBT)” in promoting a “sustainable and transparent food supply chain (STFSC)” and increasing “supply chain efficiency (SCE)”. Moreover, the outer loadings suggested strong reliability of constructs with all factor loadings above 0.7. Apart from that, the “collinearity statistics (VIF)” range between 1.754-3.830, indicating the absence of multicollinearity problems. Subsequently, the highest outer loadings of 0.897 for SCI4 and 0.910 for BBT4 suggested the strongness 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.

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 alphas scores were above 0.7, which were in the range of 0.885 to 0.888, reflected 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 varieties 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 food supply chain thereby increasing its potentials in building stakeholder's trust.

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

Similarly, the correlation matrix indicated the interconnections among BBT, DDS, SCE, SCI, STA, and STFSC. There was also suggested the square root of the AVE in diagonal values with all exceeding at 0.7, which indicates strong discriminant validity. Furthermore, high correlations are present between SCE and SCI (0.846) and STFSC and SCE (0.859), focusing on the role of smart contracts and supply chain efficiency in sustainability. Simultaneously, STFSC and BBT (0.799) highlighted the significance of traceability in increasing transparency. Meanwhile, correlations among constructs were important, none exceeded their respective AVE's square root, ensuring discriminant validity. Although these results indicate that blockchain block chain solutions offer opportunities to create more sustainable and efficient, as well as, trusted food supply chains, and reinforce the need for smart contracts and decentralized security in building trust and transparency among the stakeholders.

3.3 Inner Structural Model

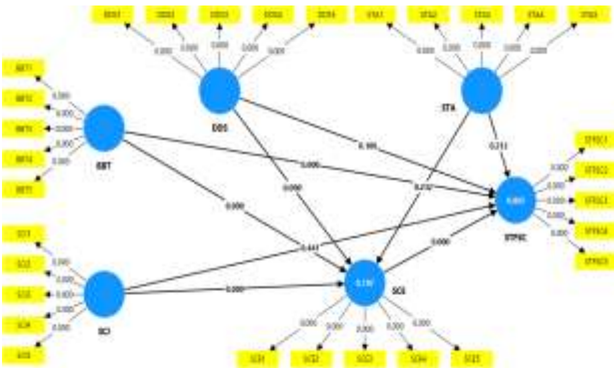

Figure 3. *Inner Structural Model*

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

Significantly, the results of hypothesis testing lend support that SCI, DDS, and BBT have a significant influence on STFSC and SCE. In particular, BBT affects both STFSC (p = 0.000, β = 0.399) and SCE (p = 0.000, β = 0.218) positively and so exerts an effect to improve transparency. Similarly, DDS had a remarkable effect on STFSC (p = 0.001, β = 0.209) and SCE (p = 0.000, β = 0.273). Besides these, SCI exhibited strong impacts on STFSC (p = 0.008, β = 0.261) and SCE (p = 0.000, β = 0.420). Moreover, STA did not significantly affect STFSC and SCE. Subsequently, mediation analysis confirmed the indirect influence of SCT, DDS, and BBT on STFSC through SCE. So, these results focused on blockchain technologies' critical role in increasing supply chain efficiency and sustainability while suggesting a limited direct impact on stakeholder trust**.**

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 introduced that 80.2% of variances of STFSC and 78.7% of variances 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, these 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 besides this. 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.

4. Discussion

4.1 Introduction

The discovery of this study is relevant as it shows the potential that blockchain technology can occur 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 enhanced significantly the effectiveness of the supply chain with its capacity in raising 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 availability 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.

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 purchase 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 sources 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.

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 environment friendly practices without sacrificing on the profitability and efficiency[40]. However, blockchain by offering accurate data on resource utilization assisted firms to minimize their carbon footprint, reduce waste, and optimize 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 extra 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 uses, and sustainable farming methods adoption, contributing to the entire 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

Finally, blockchain technology is transforming food supply chains by fostering sustainability, promoting trust, and increasing efficiency. In addition, the ability to food products practically confirmed seamless supply chain coordination and accurate inventory management, improving responsiveness and reducing inefficiencies. Smart contracts and blockchain-powered traceability increased ethical sourcing and trust by offering verifiable proof of supplier compliance and product authenticity. Significantly, blockchain-driven sustainability initiatives assisted companies in supporting environmentally friendly sourcing practices, optimizing resource utilization, and reducing waste. As the adoption of blockchain continues to develop, the supply chains of food are becoming more resilient, efficient, and transparent, confirming long-term success and growth in a growingly competitive market.

5. Conclusions

5.1 Conclusions

To summarize, the processing of the food supply chain using blockchain technology can turn the present-day process into an even more sustainable, transparent, and efficient one therewith. Through advancements of smart contracts, real-time coordination and blockchain based traceability, businesses can ensure a frictionless communication, get rid of inefficiencies and coordinate processes throughout the advancements. However, these advancements remarkably optimize overall productivity, minimize delays, and improve inventory management. Subsequently, blockchain promoted accountability and trust by offering verifiable proof of ethical sourcing, supplier compliance, and product authenticity. Moreover, customers growingly demand transparency in the production of food, and blockchain technology confirmed adherence to fair-trade, safety, and quality standards. Blockchain by offering sustainable framing methods and ethical labor practices encouraged responsible business practices and strengthened consumer confidence.

In addition, sustainability has a beneficial role in blockchain implementation, as it assists companies minimize their environmental influence, reducing food waste, and optimize resource utilization. Blockchain by supporting eco-friendly sourcing, enhancing demand forecasting, and tracking food expiration dates contributed to long-term sustainability while maximizing profitability. In addition, it has seen a clear role for the technology in reshaping food supply chains that will ultimately result in more sustainable, trustworthy and efficient food supply chains. Yet, as blockchain adoption continues, the competitive market will benefit, innovation will occur, and companies will be able to meet consumers' changing expectations in support of a responsible and resilient food system on a global scale.

5.2 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 in order 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’s a need to clearly set regulatory frameworks that allow the use of blockchain, yet that conforms 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]. Also, the smart contracts can be utilized to confirm fair trade practices and ensure sustainability commitments. In addition, the need for the collaboration of research institutions, government agencies and players from the industry for the promotion of blockchain innovation is emphasized. Significantly, encouraging pilot projects and partnerships will allow companies to refine and test blockchain applications, confirming long-term success and scalability[48]. So, food supply chains by adopting these recommendations, can fully harness the potential of blockchain, increasing sustainability, trust, and efficiency while staying competitive in a growing and changing market.

5.3 Limitations of the study

While this research offers a great deal of knowledge that helps to comprehend the use of blockchain in managing the food supply, it has some limitations. The first issue is as a quantitative research study depending on surveys, the results relied on self-reported data that potentially led to misinterpretation by respondents or bias [49]. Additionally, the responses' accuracy depends on the experience and knowledge of participants with blockchain technology, possibly affecting the results' reliability. Besides these, this study is restricted by geographic scope and sample size, potentially limiting the findings' generalizability to a wider population. Generally, the adoption of blockchain and its influence on supply chains can vary across company sizes, industries, and regions, and need further investigation and comparative analysis. Next, blockchain technology is quickly changing and new developments influenced its effectiveness and adoption in supply chains [50]. Furthermore, the results of the study were contingent upon current developments that could have changed over time. Results on the last position include challenges of resistance to change among stakeholders, regulatory uncertainties, and high implementation costs which are not deeply investigated. Hence, future study must include these facets to provide a detailed understanding of blockchain's value in food supply chains on a day-to-day basis [51].

5.4 Future Perspectives

In terms of food supply chain management, however, blockchain's future is very bright due to its sustainability, efficiency and innovation potential. Additionally, with continuously evolving technology, it is possible to advance more compatibility with IoT and AI, transforming its ability to automate decision making, predictive analytics and to track on real time basis. For instance, these advancements subsequently will allow proactive management of the supply chain that enhances resource allocation as well as minimizes waste. Regulatory developments also will influence the use of blockchain in food supply chains. Industry bodies and governments introduced policies mandating traceability and transparency, accelerating the implementation of blockchain across global markets. In addition, future research needs to investigate the regulatory landscape and its influence on blockchain adoption. Moreover, as consumers and businesses become more aware of sustainability and ethical sourcing, blockchain can play an essential role in verifying compliance with environmental standards and fair trade. Lastly, future studies need to examine the way blockchain-driven sustainability initiatives influence business strategies and consumer behavior. Overall. Blockchain is composed to transform food supply chains, making them more resilient, efficient, and transparent.

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Abbreviations

The following abbreviations are used in this manuscript:

FSC	Food Supply Chain
BBT	Blockchain Based Traceability
SCI	Smart Contract Implementation
DDS	Decentralized Data Security
STA	Stakeholder Trust and Adoption
STFSC	Sustainable and Transparent Food Supply Chain
SCE	Supply Chain Efficiency
AI	Artificial Intelligence
IoT	Internet of Things
DLT	Distributed Ledger Technology
TCT	Transaction Cost Theory
RBV	Resource-Based View
IDT	Innovation Diffusion Theory
SLR	Systematic Literature Review
WHO	World Health Organization
ASC	Agriculture Supply Chain
SEM	Structural Equation Modelling
IRB	Institutional Review Board
EFA	Exploratory Factor Analysis
VIF	Collinearity Statistics
AVE	Average Variance Extracted

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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