# Unlocking the Potential: Leveraging Blockchain Technology for Agri-Food Supply Chain Performance and Sustainability

**Abstract**

**Purpose** – Blockchain technology (BCT) has emerged as a powerful tool for enhancing transparency and trust. However, the relationship between the benefits of BCT and agri-food supply chain performance (AFSCperf) remains underexplored. Therefore, the current study investigates the influence of BCT on AFSCperf and sustainability issues.

**Design/methodology/approach** – Through a comprehensive literature review, various benefits of BCT are identified. Subsequently, a research framework is proposed based on data collected from questionnaire surveys and personal visits to professionals in the agri-food industry. The proposed framework is validated using partial least square structural equation modelling (PLS-SEM).

**Findings** – The findings reveal that BCT positively impacts AFSCperf by improving traceability, transparency, food safety and quality, immutability, and trust. Additionally, BCT adoption enhances stakeholder collaboration, provides a decentralised network, improves data accessibility, and yields a better return on investment, resulting in the overall improvement in AFSCperf and socio-economic sustainability.

**Practical implications** – This study offers valuable practical insights for practitioners and academicians, establishing empirical links between the benefits of BCT and AFSCperf and providing a deeper understanding of BCT adoption.

**Originality/value** – Stakeholders, managers, policymakers, and technology providers can leverage these findings to optimise the benefits of BCT in enhancing AFSCperf. Moreover, it utilises rigorous theoretical and empirical approaches, drawing on a multidisciplinary perspective encompassing food operations and supply chain literature, public policy, information technology, strategy, organisational theory, and sustainability.

***Keywords***: Blockchain technology; Agri-food industry; Supply chain performance; Sustainability; Transparency; Traceability

## 1. Introduction

The agri-food supply chain (AFSC) is complicated, involving the management of agri-food commodities from growers to consumers (Afrianto et al., 2020; Astill et al., 2019). An efficient supply chain requires a collaborative environment among stakeholders characterised by mutual trust, effective communication, and multi-party collaboration (Durach et al., 2021; Helo & Hao, 2019). Over the past few years, the agri-food sector has experienced significant growth due to globalised business, distributed production, and diversified product portfolios (Rejeb et al., 2020). Consequently, the traditional AFSC has transformed into a network of multi-party stakeholders producing and distributing a wide range of products (Vern et al., 2024). Consumers need to know the product safety, quality, and sustainability as AFSC has become complex (Behnke and Janssen, 2020). Traditional AFSC faces various challenges, including a need for more transparency and traceability in food products, information asymmetry, food safety issues, and stakeholder trust. These challenges directly undermine consumer trust in AFSC management (Demestichas et al., 2020). Moreover, in traditional AFSC, trust and performance are critical due to the involvement of multiple stakeholders (Rana et al., 2021a).

To overcome these issues and improve performance, the AFSC is exploring emerging disruptive technologies, such as Blockchain Technology (BCT), the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Robotics, etc. (Vern et al., 2023; Mor et al., 2021). Implementing advanced technologies can improve supply chain transparency, traceability security, and information exchange (Quayson et al., 2021). Among these technologies, blockchain is a promising solution that addresses various challenges and enhances AFSCperf. BCT functions as a distributed ledger that records all transactions, with consensus reached among all participants through a consensus mechanism (White, 2017). It is an immutable digital ledger with trustworthy records arranged as interconnected data blocks (Rana et al., 2021b). The blockchain system ensures high security by utilising a decentralised and cryptographically secure transaction mechanism for block formation and verification. BCT offers a viable solution for achieving end-to-end traceability (Cole et al., 2019). It facilitates the tracking of shipments, confirmation of origin and locations, and provides transaction proofs within a decentralised system (Helo & Shamsuzzoha, 2020).

Saurabh & Dey (2021) highlighted the need to adopt transparent and sustainable methods for agri-food production and certification, increasing consumers' perceived value and willingness to pay for healthy foods. A review conducted by Rana et al. (2021a) concluded that blockchain positively contributes to the sustainability of agri-food production. BCT's data immutability, transparency, and traceability capabilities improve the connection between eco-friendly standards and supply chain sustainability practices (Castillo et al., 2024). Existing information asymmetry hinders the process of achieving sustainable goals. Implementing BCT in AFSC can help to achieve information symmetry and sustainable goals like SDG 1- no poverty, SDG 3- good health and well-being, SDG 5- Gender equality, SDG 8- decent work and economic growth, SDG 12- responsible consumption and production, SDG 14- life below water (Tsolakis et al., 2021). BCT plays a vital role in achieving SDG -2 (Ending hunger) through improved food security and nutrition as well as SDG-12 by ensuring sustainable consumption and production (González-Puetate et al., 2022; Wünsche & Fernqvist, 2022). Nurgazina et al. (2021) conclude that blockchain technology potentially contributes to sustainability in food supply chains and sustainable development goals in health, economy, decent work, waste reduction, sustainable water management, and social inclusion. BCT securely integrates the supply chain actors and facilitates identifying the sources of food adulteration and food fraud, addressing food safety issues, and quality management. Therefore, reducing social chaos enhances overall sustainability in the supply chain process (Dutta et al., 2020). The application of BCT supports production information provision, which contributes to data collection, exchange, and analysis, enhancing overall operational efficiency and sustainability (Liu et al., 2021). Also, integrating IoT and BCT leads to smart agriculture, improving the sustainability of supply chains (Friha et al., 2021; Song et al., 2021). A blockchain-enabled e-agriculture system can help create a sustainable agri-food supply chain structure (Li X et al., 2020; Song et al., 2020).

Further, blockchain can also be implemented commercially to track fish from the sea to the tuna cans to help fishers verify social sustainability claims (Antonucci et al., 2019). Mercuri et al. (2021) studied the impact of BCT on the sustainability of agri-food business models using a case-study approach. Devoleum, an Italian start-up, utilises a decentralised solution to attain traceability at all phases of AFSC operations using Ethereum blockchain and AI. Findings demonstrated that BCT can lead to sustainability through traceability. Similarly, Walmart partnered with the IBM food trust system to implement BCT to track the origin and movement of food products within the supply chain to boost food safety and attain social sustainability (Helo and Hao, 2019). Yadav et al. (2020) developed a data-driven framework for measuring AFSC performance based on IoT and included sustainability as a metric. Blockchain-based technologies can facilitate the tracking of sustainability certificates while lowering the need for audits due to improved information quality and accessibility (Köhler and Pizzol, 2020).

Thus, literature shows that technological advancements like blockchain technology have great potential in addressing sustainability issues in agri-food supply chains in developing countries. The benefits of implementing BCT in AFSC are that it helps enhance sustainability (Yew et al., 2020). Environmental sustainability is managed by managing waste; social and economic sustainability is managed by protecting consumer welfare and minimising costs (Park & Li, 2021). The literature suggests that integrating BCT into the AFSC is a robust and trusted approach to modernise supply chain operations to enhance its performance, sustainability, and technological interventions.

While many recent studies have focused on the benefits of BCT in the AFSC field, only a few have examined the impact of these benefits on agri-food supply chain performance (AFSCperf). In line with this, the current research aims to bridge this knowledge gap identified in the literature by understanding and examining blockchain's value to the Indian AFSC. The primary objective of this study is to validate the benefits of BCT and its influence on AFSCperf. The study addresses a research question (RQ), i.e., *Does blockchain technology positively impact the Indian agri-food supply chain performance?* To answer the RQ, we identified the benefits of BCT in the AFSC through a literature review. Subsequently, a research framework was proposed to investigate and validate the relationship between BCT and AFSCperf. The proposed research framework was then tested using data collected through a survey questionnaire in India. This study contributes to the literature on BCT, AFSC, and related areas, providing empirical evidence to managers regarding the worth that blockchain offers in enhancing supply chain performance. Additionally, the results validate the proposed framework from a theoretical standpoint, creating further research opportunities for scholars to explore these relationships in greater depth.

The structure of the remaining paper is as follows: The next section provides an overview of the emerging literature on BCT in AFSC and discusses the role of BCT and AFSCperf. A discussion on the problem formulation follows this. Subsequently, we explain the materials and methods employed in the study, followed by the presentation and discussion of the results. Finally, the study concludes by offering theoretical and managerial implications.

## 2. Literature Review

### *2.1. Blockchain technology*

Blockchain technology is a distributed ledger that both parties can digitally verify. This ledger documents data about the generation, transaction and consumption of products and services (Kramer et al. 2021b). The first block in the chain, known as the genesis block, along with subsequent blocks, is stored on the Merkle tree schema, with transactions recorded on leaf nodes (Nawari & Ravindra, 2019). The distributed database maintains a chronological arrangement of all network information in blocks. Each record in the blocks includes a timestamp and an encrypted reference to the previous blocks by storing the hash code of the last block in the current block header (Philsoophian et al., 2021). By applying a cryptographic function to the hash code of the previous blocks, the current block number, the data in the current block, and a nonce (number only used once), the hash code for the current block is generated (Queiroz et al., 2019). Using hash codes ensures data immutability on the blockchain (Yadlapalli et al., 2022). This means that all involved stakeholders validate the data, and once a consensus is reached, the data cannot be modified or altered (Galvez et al., 2018). This distributed ledger system leverages the advantages of decentralised governance, addressing the issues of sensitive information exposure and accountability (Chang & Chen, 2020). It eliminates the need for a centralised trust authority and instead creates a trusted environment for stakeholders, reducing friction in the transaction process (Kamble et al., 2019). The emergence of BCT brings the potential for revolutionary changes to the design of business operations, leveraging its distributed and decentralised benefits (Mendling et al., 2018). The subsequent sub-section describes the role of BCT and its potential benefits in the AFSC.

### *2.2. Blockchain technology in the agri-food supply chain*

The Council of Supply Chain Management Professionals defines supply chain management (SCM) as the "*planning and managing activities involving sourcing and procurement, conversion, and logistics management. It also includes coordination and collaboration with channel partners such as suppliers, intermediaries, outsourcing, or customers"* (Kamble et al., 2019). Recently, BCT has garnered attention in SCM as a technology enabling secure and transparent information exchange among stakeholders (Aldrighetti et al., 2021). BCT is considered one of the promising digital technologies that will transform the traditional AFSC into a modernised version (Duan et al., 2020; Holmström et al., 2019). Its inherent benefits in the AFSC encompass secure, efficient, and transparent transactions and enhanced trust and reliability among supply chain participants by sharing operational information (Etemadi et al., 2021).

The benefits of BCT in the AFSC include transparency, traceability, decentralisation, smart contracts, reduced transaction costs, immutability, trust, efficient food recalls, and improved food safety and quality (Mavilia & Pisani, 2022: Kayikci et al., 2021; Rejeb et al., 2021). BCT functions as an information management system that differs from traditional approaches. It serves as a database where information is validated by each stakeholder in a peer-to-peer manner, creating a decentralised database (Perez et al., 2020). Peer-to-peer data validation establishes a trust mechanism that enhances transparency and reduces information asymmetry (Feng et al., 2020). Additionally, BCT aids in the traceability of food products and fosters a transparent AFSC, thereby building trust among consumers and stakeholders (Enescu & Ionescu, 2020). By increasing transparency and accountability in supply chains, BCT also plays a critical role in ensuring food safety (Vivaldini, 2021). Moreover, BCT is adaptable and improves operational efficiency (Gurtu & Johny, 2019). It mitigates uncertainty by providing precise real-time information, enabling swift responses to the changing AFSC conditions (Lezoche et al., 2020).

### *2.3. Blockchain and agri-food supply chain performance*

The research defines supply chain performance as an overall performance measure determined by the performance of different stages within the supply chain (Autry et al., 2014). Price, cost reduction, and the quality of agri-food products are considered factors enabling the examination of AFSC performance (Bhat & Jõudu, 2019). Using blockchain-based food supply chains can help build trust among stakeholders involved in manufacturing, processing, and delivery (Fortuna & Risso, 2019). It can also enhance consumer awareness and confidence in product safety, quality, and authenticity (Tse et al., 2017). Lezoche et al. (2020) discovered that integrating BCT allows agri-food organisations to obtain real-time information and enhance their supply chain performance. Ali & Govindan (2021) also found a positive influence of disruptive technologies on mitigating risks in the AFSC, leading to superior firm performance. Paul et al. (2021) revealed a positive association between the sustainable performance of the organic tea supply chain and BCT using Structural Equation Modelling (SEM). Mangla et al. (2022) presented an integrated blockchain and sustainable tea supply chain framework for the possible risks. Zhao et al. (2019) contributed to the literature by conducting a systematic literature review to study the potential of BCT in the AFSC, and the findings indicated that BCT improves AFSCperf by enhancing food safety, quality, and traceability.

Kramer et al. (2021a) conducted exploratory interviews and concluded that BCT plays a mediating role in positively impacting the performance of the AFSC. Tipmontian et al. (2020) used a system dynamics approach and found that adopting BCT could enhance customer awareness, transparency, and traceability. It also helps in reducing food fraud and the associated costs. Furthermore, BCT dimensions can improve food value chain performance and AFSC. Stranieri et al. (2021) study explored the impact of BCT on AFSCperf using a set of performance dimensions, and the results revealed a positive impact on food quality attributes, return on investment, and better information management by enhancing information availability, accessibility, and sharing, thus enhancing transparency along the supply chain. Saurabh and Dey (2020) used conjoint analysis to understand the link between BCT drivers and stakeholders' adoption intention. The study found that dis-intermediation, a characteristic of BCT, was perceived as a significant factor, followed by traceability, compliance, price, coordination, trust, and control, all of which could improve AFSCperf.

In the following section, various hypotheses are derived, and a conceptual research framework is proposed to unlock and develop a better understanding of the relationship between BCT and AFSCperf.

## 3. Development of Hypotheses and Research Framework

It is evident from the existing literature that the role of BCT has been explored in various dimensions. However, despite the extant literature related to BCT, a significant knowledge gap still exists. Existing literature emphasises the benefits of BCT (Aldrighetti et al., 2021), barriers (Feng et al., 2020), frameworks (Chandra et al., 2019), its impact on sustainability (Dutta et al., 2020), and the circular economy (Khan et al., 2021). Previous studies have attempted to examine the link between BCT adoption and performance for supply chains (Nayal et al., 2021), the circular economy to improve organisational performance (Khan et al., 2021), supply chain partnerships and performance (Kim & Shin, 2019). However, to the authors' knowledge, limited research has been conducted to uncover the value BCT can add to AFSCperf. Wamba et al. (2020) also emphasised the need for more robust and empirical studies to understand the relationship between the benefits of BCT and supply chain performance. Therefore, this research bridges the identified gap by offering an empirical analysis of the relationship between the benefits of BCT and AFSCperf. The study has identified six significant benefits of BCT, and the following hypotheses are established and presented in Figure 1.

### *3.1 Traceability and transparency*

Traceability refers to the ability to recall information about the product's origin (Demestichas et al., 2020), while transparency relates to access to factual, relevant, and timely information about supply chain operations and food products (Astill et al., 2019). Traditional supply chains face difficulties at various stages, such as late deliveries, fraudulent acts like spoilage and theft, contamination, and issues that are challenging to detect through visual checks (Zailani et al., 2019). BCT is argued to be the solution to address these issues (Kamble et al., 2020). Previous studies have suggested that BCT can increase transparency and traceability in AFSC (Mukherjee et al., 2021; Tan et al., 2020). BCT records each transaction, and real-time data capture allows for the supervision of food products throughout the supply chain (Chen et al., 2020). AFSC performance can be enhanced with BCT by increasing transparency and traceability (Ali et al., 2021; Kamble et al., 2020), thus leading to economic sustainability (Bosona & Gebresenbet, 2023). Therefore, the study hypothesises that:

***$H_1$*: *Traceability and transparency positively influence agri-food supply chain performance.*

### *3.2 Smart contracts*

Smart contracts are computerised transaction protocols that implement the terms of a contract (Pranto et al., 2021). These scripts are stored in the blockchain and identified by a specific address (Prashar et al., 2020), which translates contractual clauses into code and embeds them into hardware and software, allowing the code to run independently (Kramer et al., 2021b). Smart contracts are designed to share predefined conditions, such as rules, penalties, and actions applied to the parties involved (Dutta et al., 2020). This eliminates the need for trusted intermediaries. BCT enables transparent tracking of food products from production to consumption, and a smart contract ensures that all the requirements for consumption are met (Perez et al., 2020). Wamba et al. (2020) suggested studying the impact of BCT-enabled smart contracts on supply chain performance. Thus, the study proposes the following hypothesis:

**$H_2$:** *Smart contracts positively influence agri-food supply chain performance.*

### *3.3 Immutability*

BCT is a distributed ledger in which each block captures the details of a record, and transactions are encrypted and permanently stored in the chain (Sudha et al., 2021). The data entered into the BCT network is immutable and secured using cryptographic hash functions, ensuring that it cannot be changed or tampered with (Ekawati et al., 2021). This eliminates common issues of maintaining digital records, viz., data manipulation, deletion, or tampering. Even if a transaction contains errors, it cannot be altered or destroyed. Instead, a new transaction with correct information must be added as a new block (Santhi & Muthuswamy, 2022). The immutability of data facilitates the tracking of data and transactions in chronological order with an appropriate timestamp (Nowiński & Kozma, 2017). Previous studies suggest immutability significantly benefits BCT, improving supply chain performance (Li et al., 2021). Therefore, the study hypothesises that:

**$H_3$:** *Immutability positively influences agri-food supply chain performance.*

### *3.4 Reduced costs*

The complexity of the AFSC introduces challenges, such as high-cost risks at every process step. Lack of transparency and unethical practices contribute to food fraud and recalls. Counterfeit products lead to market share losses and high supply chain costs for agri-food organisations (Chen et al., 2017). The cost of operating the supply chain is estimated to account for two-thirds of the final cost of goods (Kamilaris et al., 2019). The exchange of goods relies on complex and paper-heavy settlement processes that lack transparency. The involvement of intermediaries increases the overall costs of AFSC operations (Cong et al., 2019). Many studies suggest that adopting BCT can reduce these costs, including operating, administrative, and quality costs (Schmidt & Wagner, 2019). BCT-enabled smart contracts can replace paperwork, and transactions can be recorded on an immutable ledger (Li et al., 2021). This helps reduce the time spent on data validation, allowing more time to be utilised for delivering quality goods (Deloitte, 2017). From this perspective, we propose that BCT helps reduce overall costs and is essential for AFSC performance, especially in economic sustainability (Mercuri et al., 2021). Thus, the study hypothesises that:

***$H_4$:** Reduced costs positively influence agri-food supply chain performance.*

### *3.5 Enhanced trust*

In the agri-food supply chain, trust is considered an influential factor in igniting interest in BCT (Wang et al., 2019). Consumers increasingly demand information about the origin of their products (Rogerson & Parry, 2020). BCT enables the digitisation of product information and facilitates the sharing of details related to audits, certifications, product processing, and other relevant information (Fortuna & Risso, 2019). BCT can promote information to end consumers, thus enhancing consumer trust in AFSC operations (Lin et al., 2021; Hong et al., 2021; Feng et al., 2020). Trust also plays a vital role among supply chain stakeholders, including growers, suppliers, processors, and retailers (Baralla et al., 2019). Numerous researchers have indicated that trust is an influential factor contributing to effective AFSC performance (Rana et al., 2021(b); Mahyuni et al., 2020; Wamba et al., 2020) and a vital aspect of social sustainability in businesses (Rejeb & Rejeb, 2020). Based on this, the study hypothesises that:

***$H_5$:** Enhanced trust positively influences agri-food supply chain performance.*

### *3.6 Ensured food safety and quality*

The safety and quality of food products have become a global concern. Food safety and quality measures are taken to ensure food is safe for consumers from "farm to fork" and prevent foodborne outbreaks (Xu et al., 2020). In this context, BCT has emerged as a promising technology that enables supply chain stakeholders to efficiently record food products' origin and movement and identify or eliminate harmful food products (Treiblmaier & Garaus, 2023). BCT provides unprecedented visibility at each step of the AFSC, ensuring food safety and quality (Li et al., 2021; Westerlund et al., 2021). Using BCT in AFSC facilitates timely data sharing, such as origin, batch number and processing dates, and safety certifications (Galvez et al., 2018). Studies by Zhao et al. (2019), Stranieri et al. (2021), and Mukherjee et al. 2021 have explored the potential of BCT to enhance AFSC performance by ensuring food safety, quality, and social sustainability. Therefore, the study hypothesises that:

***$H_6$*: *Food safety and quality positively influence agri-food supply chain performance.***

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## 4. Methods

First, we conducted a literature review to identify the potential benefits of BCT in AFSC. We utilised significant research databases, including ScienceDirect (Elsevier), Springer Link (Springer), Emerald Insight (Emerald), Taylor & Francis Online (Taylor & Francis), IEEE Xplore Digital Library (IEEE), and Wiley Online Library (Wiley). A combination of keywords was used to identify factors/benefits of the technology, such as "blockchain", "blockchain technology", "agri-food supply chain", "agri-food organisation", "benefits", "advantages", or "enablers". Thorough reviews of articles related to the research goal were conducted to identify the potential benefits of BCT in the AFSC. This study finalised six benefits as primary constructs (Table A1). The research methodology for the analysis is outlined in Figure 2.

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### *4.1. Data collection*

This study employed a questionnaire survey as the data collection approach. The survey was chosen as it helps overcome geographic distances, saving time and expenses (Kamble et al., 2019). The questionnaire survey was considered an appropriate tool for this study. Thus, the questionnaire consisted of two sections. The first section includes an introduction and demographic details, such as respondents' names, designations, organisations' natures, operation areas, and implementation intentions. The second section gathered respondents' perceptions of BCT in improving AFSCperf based on the benefits of the technology. The questionnaire comprised thirty-one items that were developed after an extensive literature review. Each construct in the questionnaire was measured on a five-point Likert scale, ranging from “strongly disagree” to “strongly agree”. The questionnaire survey was emailed to technology providers and agri-food supply chain professionals.

The initial sample consisted of 550 respondents from various alum databases and LinkedIn. Participation in the questionnaire survey was voluntary, and the researchers sent two follow-up emails. All participants were ensured to be familiar with the concept of BCT and its applications in AFSC to increase the content validity of the questionnaire survey. Additionally, a video link was included within the questionnaire survey to describe BCT briefly. One hundred twenty-three India-based agri-food supply chain professionals agreed to participate in the survey, with 40% of responses collected through personal visits and the remaining through questionnaires. Twenty-seven responses were excluded due to a lack of a clear pattern and duplicate responses. Finally, a sample of 96 agri-food professionals and technology adopters from India was considered for this study. PLS-SEM can be utilised with a substantially smaller sample size, even when the models are complicated (Hair et al., 2014). Technically, this is feasible by the PLS-SEM algorithm, which computes the relationships between measurement and structural model independently rather than simultaneously. The algorithm uses separate ordinary least regression partial to compute partial regression relationship in the measurement and structural models (Hair et al., 2019). This sequential approach is considered less sensitive to sample size limitations than other SEM methodologies. Also, researchers are often advised to employ the required sample size to get reliable and accurate results (Purwanto and Sudargini, 2021). Thus, the minimum sample size requirement, as highlighted by various researchers i.e., Choi et al. (2020), suggested a sample size between 30 and 500 suitable for this research type. Purwanto and Sudargini (2021) suggested a minimum sample size between 30-50 for social and management research.

Similarly, Boubker et al. (2021) considered a sample of 98 respondents to analyse the effect of entrepreneurship education on entrepreneurial intentions using the PLS-SEM approach. Additionally, Chin (1998) and Huang (2021) suggested that PLS-SEM requires the sample size to be ten times the construct of most measurement items. The construct with the most measurement items is “Traceability and Transparency,” which is four. The minimum sample size for research must be at least 40. Thus, The sample size of this study is 96, which meets the minimum sample size requirement of PLS-SEM. The demographic details of the respondents and organisations are reported in Table A2.

### *4.2. Statistical methods*

Structural equation modelling (SEM) is extensively used in social, behavioural, and health sciences to empirically examine research data with multiple variables. SEM allows researchers to build and test hypothetical relationships among constructs and their items (Deng et al., 2018). It is considered an analytical process involving model conception, construct identification and estimation, and structural model assessment (Mueller et al., 2018). SEM consists of a two-step assessment: the measurement model assessment and the structural model assessment. The measurement model assessment determines whether data fits the given model and establishes a link between constructs and their items. The structural model identifies the interrelationships among constructs in the hypothesised model (Mor et al., 2021; Karakaya-Ozyer & Aksu-Dunya, 2018). Following SEM, this study adopted SmartPLS 3.0 software to test the proposed hypotheses (Ringle et al., 2015). PLS-SEM is gaining prominence in social science research as it works efficiently with small or large data sizes and can provide valid and reliable results (Choi et al., 2020). PLS-SEM has shown its ability to build composite structures while maintaining high prediction accuracy. It can handle complex model distributions, works well with several indicator variables, and manages non-normal data (Astrachan et al., 2014). This quality is useful for academics who want to investigate complex interactions within the model. PLS-SEM is well known for its adaptability to complex model distributions, which increases its relevance to a wide range of research scenarios (Khan et al., 2021).

Furthermore, PLS-SEM's versatility extends to its capacity to handle many indicator variables. This capability is crucial when dealing with complex models integrating many indicator variables to adequately represent underlying components (Khan and Yu, 2020). PLS-SEM does not assume the data distribution and works efficiently with non-normally distributed data (Al-Emran et al., 2019). Another reason for adopting PLS-SEM is that it can handle both reflective and formative measurement models, as well as constructs with single and multiple-item measurements. (Hair et al., 2019). The developed framework for this study is a reflective model. Additionally, PLS-SEM is appropriate for exploratory research (Queiroz and Wamba, 2019).

## 5. Data Analysis and Results

This section presents the results and analysis obtained from the SmartPLS 3.0 software. The first part discusses the findings of the measurement model assessment, and the sub-section offers the findings of the structural model assessment. This study assessed the measurement model based on Hair et al. (2019) guidelines. The measurement model examined the reliability and validity between constructs and their items, including reflective indicator loadings, internal consistency reliability, convergent validity, and discriminant validity. Reflective Indicator loadings, often referred to as outer loadings or factor loadings, were tested to assess item reliability. Internal consistency reliability was measured using composite reliability and Cronbach's alpha. Convergent validity was evaluated using Average Variance Extracted (AVE). Discriminant validity was tested using the Fornell and Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio.

Next, the study evaluated the structural model, which involved testing Variance Inflation Factors (VIF) to check for collinearity issues, coefficient of determination ($R^2$), blindfolding-based cross-validated redundancy measure ($Q^2$), and statistical significance. SEM has been adopted to analyse and validate the relationship between variables and has proven to be a valuable tool for data analysis in emerging subjects such as BCT (Wamba & Queiroz, 2020).

### *5.1. Assessment of measurement model*

Four key steps were undertaken to assess the measurement model. Firstly, the study evaluated the reliability of the items' by examining reflective indicator loadings and internal consistency reliability using Joreskog's composite reliability and Cronbach's alpha (Choi et al., 2020). Next, the study measured convergent validity using the AVE. Finally, discriminant validity was assessed using Fornell-Larcker's criteria and the HTMT ratio.

The values of the outer loadings between constructs and items are presented in Table 1. Reflective indicator loadings represent the direction and degree of association between latent constructs and observed indicators. The degree to which latent constructs influence or explain the observed indicators is shown by reflective indicator loadings. Higher outer loadings reflect a strong relationship between latent constructs and observed indicators. It is essential for assessing the reliability and validity of the measurement model. It ensures that the observed indicators effectively reflect the latent constructs and significantly contribute to the overall model fit. The threshold for factor loadings of all the observed indicators must be significant and above 0.7 (Hair et al., 2014). Analysis of the study revealed that outer loadings are above 0.7, which is considered satisfactory, and the results indicate that the constructs account for over 50% of the variance in the items, demonstrating adequate item reliability.

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Next, the internal consistency reliability of the constructs was assessed using Cronbach's alpha and composite reliability. Composite reliability was measured. It indicates how well the observed indicators within a latent construct collectively measure the underlying construct. Table 2 shows that the composite reliability of all constructs is above 0.7, indicating a strong internal consistency reliability of the constructs (Lin et al., 2021). Similarly, Cronbach's alpha was also measured. The Cronbach's alpha value ranges from zero to one, with a value closer to 1 indicating higher internal consistency among variables. The acceptable ranges of alpha value are > 0.9 means excellent; > 0.8 means good; > 0.7 is acceptable; >0.6 is questionable; >0.5 is poor; and <0.5 is unacceptable (Choi et al., 2020). Table 2 represents the consistency of each construct. All constructs have acceptable and excellent consistency. The study examined two types of validity: convergent validity and discriminant validity. Convergent validity was established when the constructs identified in the literature exhibited statistically significant correlations with the items. It is the degree to which a construct converges to explain the variance of its measurement items (Khan et al., 2021). The study assessed convergent validity using the AVE for which the acceptable range is 0.5 or above (Hair et al., 2019). According to the analysis, each construct in the study has an AVE value of 0.5 or above, indicating strong convergent validity (Table 2).

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Discriminant validity assesses the strength of relationships between constructs and their items. It confirms that reflective constructs exhibit stronger relationships with their items than others (Hair et al., 2021). Discriminant validity was evaluated using the Fornell and Larcker metric and HTMT ratio. Fornell and Larcker (1981) proposed a measure to test discriminant validity that each construct's AVE should be greater than any other square inter-construct correlation of the same constructs. Table 3 shows that the square root of the AVE for each construct exceeded the inter-construct correlation, which indicates that discriminant validity is within the acceptable range.

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Discriminant validity was assessed using the HTMT ratio of correlations, for which the acceptable value should be below 0.90 (Wamba et al., 2020). The HTMT ratio values for discriminant validity are presented in Table 4, indicating that discriminant validity is within the acceptable range. The results demonstrate that the model exhibits robust validity and reliability.

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After obtaining satisfactory results from the measurement model, the next step in assessing PLS-SEM results is to evaluate the structural model. The subsequent section discusses the assessment of the structural model.

### *5.2. Assessment of the structural model*

The structural model, representing the hypothesised paths in the research framework (Figure 3), was assessed using Partial Least Squares Structural Equation Modelling (PLS-SEM) with the dedicated software application.

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The assessment criteria for the model include the coefficient of determination ($R^2$), predictive relevance ($Q^2$), and significance of paths. Before evaluating the structural correlations, collinearity statistics (VIF) values were calculated. A VIF value above 10 indicates collinearity, while a value below five is acceptable (Choi et al., 2020). Table 5 presents the VIF values for the constructs, all below five, indicating acceptable collinearity.

---------- *Insert Table 5 approximately here* -------------

Next, the model is evaluated by examining the $R^2$ value of the constructs. $R^2$ (R-square) represents the variance explained by each endogenous factor and reflects the model's explanatory power (Shmueli & Koppius, 2011; Hair et al., 2019). It is also considered an in-sample predictive power (Rigdon, 2012). The $Q^2$ value, assessed through the blindfolding procedure, measures the model's predictive relevance. This procedure involves removing single points from the data matrix, replacing them with the mean, and estimating the model parameters (Rigdon, 2014; Sarstedt et al., 2014). The $R^2$ and $Q^2$ values obtained from the PLS algorithms and blindfolding are 0.743 and 0.493, respectively, indicating that the proposed model demonstrates an overall model fit. Table 6 presents the results for the formulated hypotheses, including the paths, standardised beta coefficient ($\beta$), standard deviation (SD), *t*-statistics (t), and significance level (Sig. level) (Karamchandani et al., 2021).

---------- *Insert Table 6 approximately here* -------------

The results confirm that a higher level of BCT application leads to the improvement of AFSCperf. The statistical significance of *hypotheses 1*, 3, 5, and *6* indicates that implementing BCT in an organisation can help enhance traceability and transparency, build trust, and improve food safety performance (H1:

$\beta = 0.365$; $p < 0.05$; H3: $\beta=-0.105$; $p=0.10$; H5: $\beta = 0.460$; $p < 0.05$; H6: $\beta = 0.248$; $p < 0.05$). These results demonstrate that four out of the six hypotheses were significant. However, *Hypotheses 2* and *4* suggest that BCT, specifically in terms of smart contracts and reduced costs, may not positively impact AFSCperf.

**6. Discussion**

This study proposed a framework to understand the dynamics of blockchain implementation in improving AFSCperf. BCT offers various benefits that can address issues in the agri-food supply chain. Despite being a nascent technology, especially in a developing country like India, stakeholders need a better understanding and awareness of its role in the AFSC. The findings suggest that the benefits of BCT positively influence AFSC performance, as discussed in the following section.

The study demonstrated that traceability and transparency (TT) favourably improve AFSCperf, which is consistent with Tipmontian et al.'s (2020) findings. According to the study, BCT enhances supply chain performance by allowing traceability, tracking and regulatory compliance coverage. Wamba et al. (2020) discovered a link between supply chain transparency, blockchain transparency, and supply chain performance. Traceability and transparency are important attributes of BCT as it enables members to access information within the network, allowing real-time tracking (Chang and Chen 2020; Park & Li, 2021). BCT improves the economic sustainability of AFSC through effective traceability, transparency, and efficient information sharing, enabling organisations to control the inventory towards integrated and informed business decisions and eliminate inefficiencies (Bosona & Gebresenbet, 2023).

The role of information immutability (IM) and AFSCperf has been discussed in various studies (Rana et al., 2021a; Li et al., 2021). Kim and Shin (2019) discovered that information immutability partially positively influences supply chain performance regarding operational and financial aspects. Our study empirically establishes a positive relationship between immutability and supply chain performance, indicating that BCT adoption through immutability can enhance supply chain performance (Rana et al., 2021a).

The positive association between enhanced trust (ET) and AFSCperf is also supported by the findings of Kim & Shin (2019) and Mahyuni et al. (2020). Longo et al. (2019) observed that BCT could address collaboration and trust issues, improving supply chain performance. It can improve coordination and collaboration and establish trust-based partnerships across the AFSC (Stranieri et al., 2021). Kamble et al. (2019) also explored the significance of BCT in mitigating disruptions caused by a lack of trust among stakeholders, enhancing supply chain performance. Additionally, the ability of BCT to make trustful relations among stakeholders plays a pivotal role in achieving social sustainability by promoting collaboration, ensuring fair practices, and building consumer trust (Rejeb & Rejeb, 2020).

Lastly, it was observed that the variable ensured food safety and quality (EFSQ) has a favourable influence on AFSCperf. This empirical finding is consistent with the findings of Nandi et al. (2020) and Zhao et al. (2019). Concerns regarding health-related contamination have brought significant attention to the agri-food sector. AFSC organisations could utilise BCT to verify food quality and safety throughout the supply chain to address these concerns. BCT can enhance food quality and safety by reducing food safety risks, preventing fraud, and minimising food waste (Chen et al., 2020). BCT facilitates improved food safety and quality, which contributes to the social sustainability of AFSC through auditability, continuous verification possibilities and decentralised information flow (Kshetri, 2023).

## 7. Implications

### *7.1. Theoretical implications*

This study explores and analyses the benefits of BCT in improving AFSCperf. While several studies have examined BCT's benefits, barriers, and frameworks in AFSC, few have investigated and validated the relationship between BCT benefits and AFSCperf. Therefore, this analysis provides a comprehensive framework using structural equation modelling to assess the potential of BCT. The study establishes empirical links between BCT benefits and AFSCperf, contributing to the existing literature on the topic. The statistically validated model demonstrates a high explanatory power, with endogenous constructs explaining 74.3% of the variance in AFSCperf. This research addresses the knowledge gap by empirically establishing the relationship between BCT and AFSCperf. The results highlight the perception of AFSC managers and professionals regarding the benefits of BCT in enhancing AFSCperf. The findings confirm that constructs such as TT, IM, EFSQ, and ET positively influence AFSCperf, which is consistent with previous literature on BCT benefits. This study is a foundation for future research examining the influence of BCT benefits on AFSCperf.

### *7.2. Managerial implications*

In terms of managerial implications, this research has significant implications for agri-food supply chain managers and professionals. Despite the growing literature on BCT, many agri-food businesses remain uncertain about its value in improving supply chain performance. The validated model identifies critical constructs, such as traceability, transparency, and enhanced trust, underscoring the importance of BCT in AFSCperf. The foundation helps agri-food organisations make informed decisions regarding blockchain adoption. Managers need to understand the benefits of BCT and its potential to enhance AFSC performance and operations. Understanding the link between BCT and AFSCperf is crucial for promoting blockchain adoption in the AFSC and realising its impact on the supply chain.

By enhancing traceability and transparency, BCT reduces dependency and enables tracking of food product origin, location, and movement throughout the supply chain. The secure peer-to-peer information with the immutability feature of BCT fosters trust among stakeholders, enhancing coordination and collaboration. Real-time information visibility mitigates food safety failures, facilitates efficient food recall, and reduces food wastage. Adopting BCT unlocks real-time information transparency and traceability, essential for maintaining AFSCperf. Therefore, this study provides a framework for managers to design a robust BCT-enabled supply chain. Investing in BCT with a specific budget improves reliability, visibility, and socio-economic sustainability performance.

## 8. Conclusions

Blockchain-enabled traceability and information have shown promise in addressing agri-food supply chain challenges. This research investigates the influence of BCT on AFSCperf within a research framework. The proposed framework identifies six benefits of BCT through a literature review, and Indian agri-food sector professionals validated the model. A sample of 96 respondents was collected, and the research framework was empirically assessed using the partial least square structural equation modelling (PLS-SEM) method with SmartPLS 3.0. AFSCperf can be positively influenced by BCT-enabled TT, EFSQ, IM and ET, according to the findings of this study. Also, adopting BCT can be a positive instrument for better achieving social and economic sustainability goals and improving the performance of the agri-food organisations involved. The outcome reveals that BCT can enhance sustainability by realising traceability and transparency, enhancing trust and immutability, and ensuring food safety and quality, which is particularly useful in the AFSC. The study demonstrates that adopting BCT could enhance collaboration among members, enable a decentralised network, improve data accessibility, and contribute to overall AFSC performance and socio-economic sustainability. Managers are encouraged to be aware of the advantages of BCT for the efficient management of AFSC operations. The low awareness of BCT can be attributed to its limited implementation, lack of empirical evidence on its performance enhancement and absence of standardised regulations. This study provides empirical evidence on how BCT benefits help positively influence AFSCperf. The findings may be generalised to businesses with similar settings and blockchain technology at a nascent phase; further, the infrastructure and resource availability have a vital role.

### *8.1 Future Research Directions*

Future studies can replicate this research with the same or different BCT benefits, gathering more well-defined responses from professionals in the agri-food sector. Further investigations can explore the role of various BCT benefits on supply chain performance in agri-food and related domains. Longitudinal studies can examine the long-term impact of BCT benefits on the performance of agri-food organisations, potentially utilising decision-making techniques. The relationship can also be explored in greater detail through explorative use cases. This study will assist stakeholders, managers, policymakers, and technology providers in understanding and identifying the impact of BCT on AFSCperf.

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