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Article

Blockchain technology and its influence on food supply chain transparency among small and medium enterprises

Watson Munyanyi, Raborale Isaac David Pooe*

University of Johannesburg, Johannesburg 2006, South Africa
*** Corresponding author:** Raborale Isaac David Pooe, dpooe@uj.ac.za

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Abstract: With its inherent characteristics of decentralization, immutability, and transparency, blockchain technology presents a promising opportunity to revolutionize the South African food supply chains. Blockchain technology, with its decentralized, immutable, and secure nature, offers solutions to these challenges by improving traceability and accountability across the supply chain. This study investigates the role of blockchain technology in enhancing transparency in the food supply chain among small and medium enterprises in South Africa. SMEs form a critical part of the country's agri-food sector but face challenges such as food fraud, inefficient inventory management, and lack of transparency, which impact food safety and trust. The research adopts a mixed-method approach, utilizing the Technology-Organization-Environment framework and Institutional Theory to explain blockchain adoption among SMEs. The results demonstrate that blockchain-enabled practices, such as smart contracts, records traceability, production tracking, and distribution monitoring, significantly enhance supply chain transparency. The findings highlight blockchain's potential to increase operational efficiency, regulatory compliance, and stakeholder trust. This research provides valuable insights for policymakers and practitioners, emphasizing the need for regulatory support and strategic investment in blockchain solutions to promote sustainability and competitiveness in the agri-food sector.

Keywords: blockchain technology; food supply chain transparency; traceability; industry 4.0

1. Introduction and background

Small and medium enterprises (SMEs) are the backbone and engine of the agri-food sector in South Africa, as they account for most of the food production, processing, distribution, and retailing activities in the country (Cannas, 2023; Mer and Virdi, 2024). However, SMEs face many challenges and constraints, such as a need for access to finance, technology, markets, and information, limiting their competitiveness and growth potential. Both empirical and theoretical research have confirmed that blockchain technology can provide SMEs with new opportunities and advantages (Kshetri, 2023; Li and Wang, 2024). These include reduced transaction costs, improved operational efficiency, enhanced transparency and market access, and increased customer loyalty and satisfaction. Blockchain technology is a novel and innovative way of storing and sharing data in a decentralized, distributed, and secure manner, successfully and widely applied in various domains, such as finance, health care, education, and energy (Bali et al., 2023; Mishra and Kaushik, 2023; Naef et al., 2024). However, one of the most promising and challenging areas for blockchain technology is the agri-food sector, which can enhance trust, traceability, and transparency in the food supply chain.

According to Toromade et al. (2024), the food supply chain is a complex and dynamic system that involves multiple actors, such as farmers, processors, distributors, retailers, and consumers, who interact and exchange information, products, and services. The food supply chain faces many issues and risks which affect the sector's economic, social, and environmental sustainability. Moreover, the food supply chain is influenced by various external factors, such as climate change, population growth, urbanization, and globalization, which increase the uncertainty and complexity of the system. The agri-food sector is a vital and strategic sector for the economy and society of South Africa, as it contributes to the gross domestic product (GDP), employment, food security, and poverty alleviation of the country (Raidimi and Kabiti, 2019). However, the sector also faces many challenges and risks, such as food fraud, food safety, food quality, food waste, and food security, which undermine the trust, efficiency, and sustainability of the food supply chain (Tanwar et al., 2022).

However, adopting and implementing blockchain technology in the food supply chain has challenges and limitations. Some of the barriers and obstacles include the technical complexity and scalability of technology, the lack of interoperability and standardization among different platforms and systems, the legal and regulatory uncertainty and compliance, the ethical and social implications and acceptance, and the cost and benefit analysis and evaluation (Kayikci et al., 2022; Menon and Jain, 2021). More empirical research and evidence are needed on the adoption and impact of blockchain technology in the food supply chain, especially in South Africa and SMEs. Most existing studies are conceptual, theoretical, or exploratory, focusing on blockchain technology's potential benefits and challenges in the food supply chain rather than the adoption, implementation processes, and outcomes. Moreover, most existing studies are based on the perspectives and experiences of developed countries and large corporations rather than developing countries and SMEs (Mer and Virdi, 2024; Raidimi and Kabiti, 2019; van Hilten, 2023).

Blockchain technology has rapidly expanded beyond cryptocurrencies, demonstrating transformative potential across various sectors, including finance, supply chain, healthcare, and governance. Recent studies highlight its ability to enhance transparency, security, and efficiency in diverse applications. For instance, in finance, blockchain is revolutionizing traditional banking by enabling secure, transparent peer-to-peer transactions and reducing transaction costs (Zhang and Lee, 2023). Additionally, decentralized finance (DeFi) platforms are gaining traction, allowing users to engage in lending, borrowing, and trading without intermediaries (Khan et al., 2023). In supply chain management, it improves traceability and authenticity of goods, thereby reducing fraud and ensuring ethical sourcing (Kshetri, 2023). Blockchain's immutable records also streamline compliance with regulatory standards across industries, leading to improved auditability (Li and Wang, 2024). With its inherent characteristics of decentralization, immutability, and transparency, blockchain technology presents a promising opportunity to revolutionize the South African food supply chain for SMEs. According to Cozzio et al. (2023), this technology allows for transparency across the value chain as it tracks a product's origin, location, and history. Moreover, in the healthcare sector, blockchain facilitates secure patient data sharing, drug traceability, and efficient clinical trials, enhancing data privacy while combating counterfeit pharmaceuticals (Patidar and Rathore, 2023). As organizations explore blockchain's capabilities, its adoption is expected to drive innovation and efficiency across multiple domains, highlighting its potential to redefine industry practices. Manual and paper-based record-keeping systems are prevalent among SMEs, leading to errors, delays, and susceptibility to fraudulent activities, and these outdated methods make it challenging to maintain accurate and real-time records of transactions, shipments, and quality control measures (Elahi et al., 2024).

The agri-food sector in South Africa is vital to the country's economy, yet it faces challenges such as fragmented supply chains, limited traceability, and food safety concerns that affect consumer trust and export competitiveness. Compared to countries like the Netherlands and Australia, which have successfully integrated blockchain technology to enhance transparency and efficiency, South Africa lags in adopting digital solutions due to limited infrastructure and digital literacy (Thompson, 2024). In these countries, blockchain has streamlined processes, enabled real-time production tracking, and utilized smart contracts to automate agreements, thereby improving food safety and reducing fraud (van Hilten, 2023). For South Africa, implementing blockchain for smart contracting, records traceability, and distribution monitoring could significantly enhance transparency and accountability in the food supply chain. However, overcoming barriers like regulatory constraints and technology adoption will be essential for realizing these benefits.

2. Problem statement

In the South African food industry, particularly within the SME domain, there needs to be more transparency and traceability in the supply chain, and the prevailing level of opacity poses many challenges. These challenges range from inefficient inventory management to compromised food safety, and as such, SMEs, which form a substantial portion of the food supply chain, struggle to establish robust systems that can ensure the transparency and accountability necessary for maintaining the integrity of the entire supply chain (Razak et al., 2023). Several key issues contribute to this problem, including limited visibility, ineffective record-keeping fraud, and counterfeiting and compliance challenges. Many SMEs in the South African food industry need more comprehensive visibility into the various stages of the supply chain. This limited transparency hinders their ability to identify inefficiencies, track the origin of raw materials, and respond promptly to potential issues such as contamination or spoilage (Gazzola et al., 2023). The absence of a secure and tamper-proof system makes the food supply chain susceptible to fraud and counterfeiting. Inadequate authentication mechanisms expose consumers to the risk of consuming substandard or misrepresented products. SMEs often need more standardized and transparent processes to meet regulatory requirements. This not only hampers their growth but also jeopardizes the overall integrity of the South African food supply chain. There is a critical need to explore and implement innovative solutions to address these issues and ensure sustainability and the food supply chain. This research aims to investigate and propose tailored blockchain-based technologies that can enhance transparency, traceability, and accountability within the food supply chain, empowering SMEs to overcome the current challenges and contribute to the overall improvement of the South African food industry.

3. Theoretical framework

This study draws on several theoretical perspectives to explain the relationship between blockchain technology adoption and transparency in the food supply chain among small and medium enterprises (SMEs) in South Africa. The Technology-Organization-Environment (TOE) framework and Institutional Theory form the foundation of the theoretical framework for this research. These theories provide a robust foundation for understanding how blockchain technology influences operational transparency, trust, and performance in the context of food supply chains.

3.1. The technology-organization-environment (TOE)

The Technology-Organization-Environment (TOE) framework, developed by Tornatzky and Fleischer (1990), is widely used to explain the adoption of new technologies in organizations. According to the TOE framework, three contextual factors influence an organization's decision to adopt and implement new technology: technology, organization, and environment. The technology aspect includes the perceived benefits, challenges, and complexity of a particular technology. In the case of blockchain technology, its decentralized, immutable, and transparent nature offers benefits such as improved traceability, fraud prevention, and enhanced collaboration in the food supply chain (Tornatzky and Fleischer, 1990). The organization factor refers to internal organizational characteristics, such as size, structure, resources, and capabilities. SMEs may face resource constraints that hinder technology adoption. However, blockchain can simplify supply chain processes and improve transparency and efficiency, making it attractive to SMEs looking to enhance competitiveness. Finally, the environment aspect includes external factors such as market conditions, regulatory frameworks, and competitive pressures. Blockchain adoption in the food supply chain is driven by increasing regulatory demands for food safety, transparency, and sustainability, as well as pressure from consumers who demand more visibility into food production processes. The TOE framework is applicable in this study because it explains how these three factors—technology, organization, and environment—interact to influence the adoption of blockchain technology in SMEs. For instance, SMEs that perceive blockchain's technological benefits (such as enhanced transparency and traceability) and have the organizational resources (such as digital infrastructure) are more likely to implement it. Additionally, environmental pressures, such as regulatory demands for traceability or customer preferences for transparency, motivate blockchain adoption as a competitive necessity.

3.2. Institutional theory

The second theoretical underpinning of this study is Institutional Theory, as proposed by Scott (1995). Institutional theory suggests that organizations do not operate in isolation; rather, their behavior is shaped by norms, values, and expectations from the broader institutional environment (Amenta and Ramsey, 2010). The institutional theory relates to the social structure aspects such as schemas, rules, norms, and routines, and it has provided the authoritative guidelines for social behavior, starting with how the aspects are created, diffused, adopted, and adapted to how then decline and become disused (Glynn and D'aunno, 2023). These institutional pressures, whether regulatory, competitive, or normative, can influence an organization's decision to adopt new technologies. In the context of the food supply chain, institutional pressures for transparency and accountability are increasing. Regulatory bodies, particularly in South Africa and globally, are focusing on ensuring food supply chains are traceable and accountable to reduce food fraud, contamination, and unsustainable practices (Hendricks and Masehela, 2024; Jacob-John et al., 2020). Blockchain technology, with its ability to provide immutable and transparent records, can help theory explain why SMEs may adopt blockchain technology as a response to regulatory pressures or competitive demands for legitimacy (Lin and Law, 2023; Phillips et al., 2023). SMEs in the food sector that adopt blockchain can differentiate themselves as compliant with emerging standards and regulatory frameworks and enhance their reputation with consumers, suppliers, and other stakeholders (Scott, 1995). For example, blockchain can help SMEs meet food safety standards by providing traceable records from farm to table, ensuring compliance with legal and regulatory requirements while improving trust with consumers who demand transparency.

In a nutshell, the theoretical framework for this study combines the TOE framework and Institutional Theory to explain the factors influencing blockchain technology adoption in SMEs within the food supply chain. The TOE framework provides insight into how internal and external factors shape technology adoption, while Institutional Theory explains the broader institutional pressures that drive organizations to embrace new technologies. These theoretical perspectives together offer a comprehensive understanding of how blockchain technology can transform transparency and operational efficiency in the food supply chain by addressing regulatory, organizational, and technological considerations. By adopting blockchain, SMEs can enhance their ability to meet institutional demands, comply with regulations, and increase competitiveness in a market that increasingly values transparency and trust in food production processes (Scott, 1995; Tornatzky and Fleischer, 1990).

4. Conceptual model and hypothesis development

To allow for effective data analysis and in line with SEM procedures, the conceptual model and the subsequent hypotheses relating to impact of blockchain technology on enhancing transparency in South Africa's food supply chain were developed. Each hypothesis is grounded in existing literature and reflects how specific blockchain features can optimize various stages of the supply chain. The subsequent sections elaborate on the relationships between these variables and establish the foundation for empirical testing.

4.1. Conceptual model

The conceptual model developed in this study aims to investigate the impact of blockchain technology on enhancing transparency in the food supply chain. The model is structured around four key hypotheses that explore how specific blockchain-enabled functionalities contribute to improved transparency. The model is depicted in **Figure 1**.

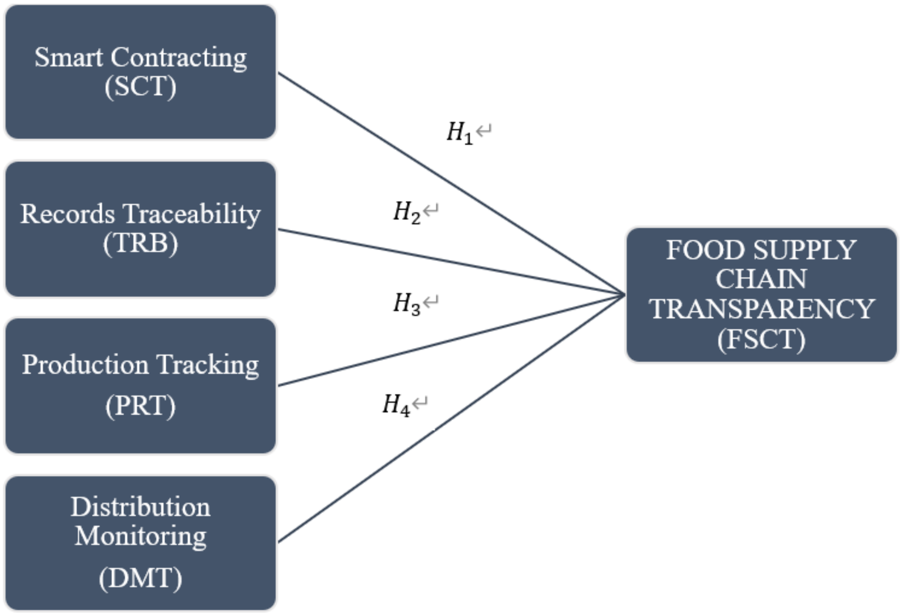

Figure 1. Conceptual model.

The conceptual model depicted in **Figure 1** aims to investigate the impact of blockchain technology on enhancing transparency in the food supply chain. The model is structured around four key hypotheses that explore how specific blockchain-enabled functionalities contribute to improved transparency.

4.2. Hypothesis development

It is generally accepted in the literature that blockchain technology can facilitate the coordination and collaboration among the supply chain actors and the enforcement of contracts and agreements using smart contracts and tokens (Agrawal et al., 2023). It is a promising and innovative technology that can potentially enhance the trust, traceability, and transparency in the food supply chain by providing a secure, distributed, and verifiable record of the food products and their origins, movements, and conditions throughout the supply chains (Menon and Jain, 2021). Blockchain technology can also enable the sharing of relevant and reliable information among the supply chain actors and the consumers, who can access the provenance and quality of the food products they purchase (Centobelli and Richey, 2021). This technology can address some of these issues and challenges by providing a transparent, immutable, and verifiable record of food products and their origins, movements, and conditions throughout the supply chain. It has been credited for enabling the sharing of relevant and reliable information among the supply chain actors and the consumers, who can access the provenance and quality of the food products they purchase (Han and Fang, 2024). In addition to the above, blockchain technology features can ensure that the entire history of a food product, from farm to table, is recorded and immutable, providing stakeholders with verifiable data on product origin, processing, and distribution. The ability to trace food items is particularly important for addressing issues such as food fraud, contamination, and recalls, as it enables faster response times and better accountability. Given the arguments presented above, the following hypotheses are made.

H1: Smart contracting positively influences food supply chain transparency.

H2: Records traceability positively influences food supply chain transparency.

H3: Production tracking positively influences food supply chain transparency.

H4: Distribution monitoring positively influences food supply chain transparency.

5. Methods

The methods section outlines the research approach used to investigate the role of blockchain technology in enhancing transparency within South Africa's food supply chain. It details the quantitative design, data collection process, sampling strategy, and analytical techniques employed to validate the conceptual model and test the study's hypotheses.

5.1. Research design

The research design for this study is a quantitative, cross-sectional, and descriptive survey aimed at understanding how blockchain technology impacts transparency and performance within the food supply chain of SMEs in South Africa. The quantitative approach was chosen because it allows for the collection of numerical data that can be analyzed using statistical techniques, providing objective, measurable results. The cross-sectional design captures a snapshot of the current situation among SMEs that are either adopting or considering the adoption of blockchain technology, allowing the study to assess correlations and patterns at a specific point in time. The research design used in this study can be summarised in **Figure 2** below.

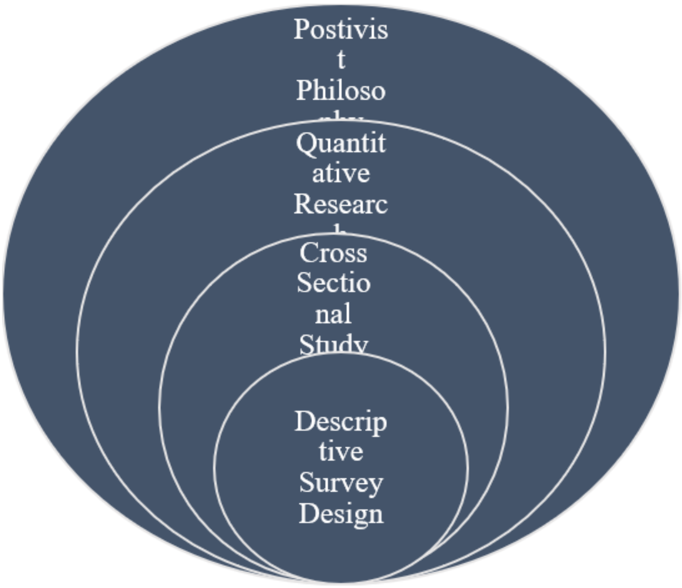

Figure 2. Research design.

By using a descriptive survey, the study seeks to describe and quantify relationships between blockchain technology adoption and various factors like transparency and supply chain efficiency. The survey format is particularly useful for gathering large amounts of data from a broad range of respondents in a relatively short time, ensuring that the findings are representative of the population being studied.

5.2. Research population and sampling

The research population consists of SMEs operating within the food supply chain in Gauteng, South Africa. These SMEs are defined according to the National Small Business Amendment Act of 2003 as enterprises employing fewer than 200 people and having an annual turnover of less than R64 million. The food supply chain is a broad sector, and this study includes SMEs involved in various segments such as production, processing, distribution, and retailing. This diversity ensures that the study captures a comprehensive understanding of how blockchain technology can impact different stages of the supply chain. Given the complexity and variation within the food supply chain, the sampling method employed in this study was a combination of non-probability convenience sampling and snowball sampling. Convenience sampling was used because it allows for easy access to respondents, especially in a sector where the adoption of blockchain technology is still emerging and may not be widespread. Snowball sampling was included to expand the sample size by asking initial respondents to refer to other SMEs they knew were using or considering blockchain technology. This method ensured that the study reached SMEs that may not have been accessible through more traditional sampling methods.

The sample size was determined using the Krejcie and Morgan (1970) formula, which is suitable for determining the appropriate sample size based on population size, confidence level, and margin of error. Given an estimated population size of 10,000 SMEs in Gauteng, South Africa's food supply chain (Omoruyi and Makaleng, 2022), a sample size of 384 SMEs was calculated to provide statistically significant results. This calculation assumes a 95% confidence level and a 5% margin of error, ensuring that the sample is representative of the broader population and that the findings can be generalized with a high degree of confidence. This dual-sampling approach was essential due to the limited number of SMEs that have adopted blockchain technology in the food sector. Many SMEs in South Africa may still be in the early stages of considering or testing blockchain applications, making it difficult to obtain a large random sample. Therefore, snowball sampling allowed the researchers to access a wider pool of relevant participants while still maintaining a representative sample of the target population.

5.3. PLS-SEM model design and analysis

To analyze the data, Partial Least Squares Structural Equation Modeling (PLS-SEM) was utilized. PLS-SEM is a flexible technique that can handle complex models with multiple constructs and indicators, particularly when the data violates normality assumptions, and the sample size is relatively small. The Dependent Variable in this study was Food Supply Chain Transparency (FSCT). FSCT refers to the degree of visibility and accessibility of information regarding the origin, production, distribution, and quality of food products (Bastian and Zentes, 2013; Menon and Jain, 2021). Supply chain transparency is a key prerequisite for sustainable agri-food supply chain management and a critical factor for enhancing transparency, trust, improving operational efficiency, and ensuring safety within the food supply chain. The independent variables influencing FSCT in this study are Smart Contracting (SCT), Records Traceability (TRB), Production Tracking (PRT), and Distribution Monitoring (DMT). SCTs are self-executing contracts with the terms of the agreement directly written into code (Zheng et al., 2020), and in the context of the food supply chain, smart contracts automate transactions and ensure compliance with predefined rules, significantly improving transparency and accountability among supply chain actors. This study employed a two-step model design to rigorously evaluate the relationships between blockchain adoption, food supply chain transparency, and performance. In the first step, the measurement model was assessed to ensure the reliability and validity of the constructs namelySCT, TRB, PRT, DMT, and FSCT. Reliability was confirmed through high Composite Reliability (CR) and Cronbach's Alpha values, while convergent and discriminant validity were established using the Average Variance Extracted (AVE) and the Fornell-Larcker criterion. The goodness of fit indices, including Standardized Root Mean Square Residual (SRMR), Comparative Fit Index (CFI) and Root Mean Square Error of Approximation (RMSEA), indicated an excellent fit between the model and the data. In the second step, the structural model was tested to examine the hypothesized relationships between blockchain adoption practices and food supply chain transparency.

5.4. Research instrument and scale development process

The research instrument employed in this study was a structured, online-administered questionnaire designed to capture data on the adoption of blockchain technology and its impact on transparency within the SMEs food supply chain of in South Africa. The questionnaire was constructed following an extensive literature review, ensuring alignment with the study's objectives and research questions. It consisted of four sections, namely, Section A: Demographic Information, which provided the basic details about the respondents and their companies, Section B: Food Supply Chain Transparency (FSCT), which provided information about the dependent variable in this study. The independent variables influencing FSCT include Smart Contracting (SCT), Records Traceability (TRB), Production Tracking (PRT), and Distribution Monitoring (DMT) and these were covered in Section C, Section D, Section E and Section F, respectively. TRB involves the ability to track and verify the history of a product throughout the food supply chain, from its origin to its destination. Records traceability ensure that stakeholders have access to accurate and timely information regarding food products, thus enhancing transparency (Pearson et al., 2019). PRT focuses on monitoring the processes involved in food production, including sourcing raw materials, quality checks, and production activities. By ensuring compliance with safety and quality standards, production tracking plays a vital role in enhancing transparency, while DMT entails tracking the conditions under which food products are transported and stored, such as temperature control and location tracking. Abass, Eruaga, Itua and Bature (2024) argue that real-time monitoring ensures that food products maintain their integrity throughout the distribution process, contributing to improved transparency in the supply chain. The questionnaire were owners and senior managers of the selected SMEs, to ensure that the information obtained about the constructs of interest is more reliable.

6. Results

The results section presents the findings from the data analysis, focusing on the impact of blockchain functionalities on enhancing transparency in the food supply chain. The outcomes of the structural equation modeling (SEM) analysis are discussed, including the evaluation of model fit indices and the testing of the proposed hypotheses.

6.1. Demographic characteristics

Table 1 provides an overview of SMEs, focusing on their size, annual turnover, provincial distribution, and sector domicile. Most SMEs (45%) employ between 0–50 people, with a further 35% having 51–100 employees, indicating that the majority are small businesses. Financially, 60% of SMEs have an annual turnover below R32 million, suggesting modest operations. Geographically, 30% of SMEs are concentrated in Gauteng, followed by 20% in the Western Cape and 15% in KwaZulu-Natal, reflecting a focus on major economic hubs. In terms of industry, 40% of SMEs are in Agri-Food, while Retail and Processing each account for 30%, highlighting a balanced sector distribution. This data paints a picture of predominantly small-scale businesses concentrated in key provinces and spread across important economic sectors.

Table 1. Demographic characteristics.

Attribute	Category	Percentage (%)	Count
SME size (employees)	0–50 employees	45	172
	51–100 employees	35	134
	101–200 employees	20	78
Annual turnover (R64 million threshold)	<R32 million	60	230
	>R32 million	40	154
Province	Gauteng	30	115
	Western cape	20	77
	KwaZulu-Natal	15	58
	Eastern cape	10	38
	Limpopo	5	19
Sector domicile	Agri-food	40	154
	Retail	30	115
	Processing	30	115

6.2. Normality test

In research, a normality test determines the extent to which sample data has been drawn from a normally distributed population (Miot, 2017). Normality was tested by examining the skewness and kurtosis values. The acceptable range for skewness is between −2 and +2, and for kurtosis between −7 and +7. The results for the normality test are shown in **Table 2**.

Table 2. Skewness, kurtosis, mean, and standard deviation for normality testing.

Variable	Mean	Standard deviation	Skewness	Kurtosis
Smart contracting (SCT)	3.82	0.74	–1.34	3.26
Records traceability (TRB)	4.10	0.68	0.98	4.12
Production tracking (PRT)	3.75	0.80	–1.45	2.89
Distribution monitoring (DMT)	4.02	0.72	1.12	3.87
Food supply chain transparency (FSCT)	3.95	0.70	–0.82	2.45

The mean values for each variable indicate that the respondents generally rated the constructs positively (on a scale likely ranging from 1 to 5), with scores around 4. This suggests a favorable view of blockchain adoption practices and transparency in the food supply chain. The standard deviations are relatively low, indicating limited variability in the responses, suggesting that most respondents had similar perceptions regarding the variables. The skewness and kurtosis values show that none of the variables follow a normal distribution. For example, Smart Contracting (SCT) and Production Tracking (PRT) exhibit negative skewness, implying that most of the ratings are concentrated at the higher end of the scale. Conversely, Records Traceability (TRB) and Distribution Monitoring (DMT) show positive skewness, indicating a clustering of responses at the lower end. The kurtosis values are all within the acceptable range for PLS-SEM analysis but still suggest non-normality, further justifying the choice of PLS-SEM as the analysis technique, which is robust to violations of normality assumptions. The kurtosis values, for instance, 3.26 for SCT and 4.12 for TRB, show non-normality, which justified the use of PLS-SEM. According to Miot (2017), researchers should exercise caution with data that do not conform to a normal distribution. In this study, the data breached normality assumptions, justifying the use of PLS-SEM. According to Hair and Alamer (2022), PLS-SEM is particularly suitable when analyzing complex models, focusing on prediction, especially out-of-sample prediction to enhance external validity, when the data deviate from normal distribution, when formative constructs are involved, and when higher-order constructs provide a deeper insight into theoretical models.

6.3. Construct and convergent validity and reliability

Construct validity refers to the degree to which a test or instrument accurately measures the theoretical concept it is intended to measure. It ensures that the measurement tool truly captures the construct it is supposed to represent. Hair et al. (2022) emphasize that construct validity is a crucial aspect of model evaluation in research, ensuring that the relationships between variables reflect the intended theoretical constructs. Convergent validity refers to the extent to which multiple indicators or measures of a construct are in agreement, meaning that they consistently represent the same underlying concept. On the other hand, reliability refers to the consistency and stability of the measurement over time. A reliable instrument will yield the same results under consistent conditions. As Cronbach (1951) highlighted, reliability is often assessed using measures like Cronbach's alpha, which evaluates the internal consistency of a set of items in a construct.

6.3.1. Construct validity

Table 3. Convergent validity results.

Construct	Item	Factor loadings (FL)	Composite reliability (CR)	Cronbach's alpha (α)	Average variance extracted (AVE)
SCT			0.886	0.89	0.666
	SCT1	0.781			
	SCT2	0.852			
	SCT3	0.825			
	SCT4	0.789			
RTB			0.884	0.87	0.665
	RTB1	0.792			
	RTB2	0.877			
	RTB3	0.764			
	RTB4	0.801			
PRT			0.896	0.85	0.684
	PRT1	0.844			
	PRT2	0.789			
	PRT3	0.832			
	PRT4	0.841			
DMT			0.910	0.86	0.717
	DMT1	0.874			
	DMT2	0.796			
	DMT3	0.818			
	DMT4	0.895			
FSCT			0.906	0.91	0.708
	FSCT1	0.891			
	FSCT2	0.810			
	FSCT3	0.878			
	FSCT4	0.782			

Construct Validity was tested using the Fornell-Larcker criterion and cross-loadings, ensuring that each construct was distinct from the others. The Fornell-Larcker criterion compares the square root of the Average Variance Extracted (AVE) of each construct with the correlations between constructs. To confirm discriminant validity, the square root of the AVE should be greater than the correlation between any two constructs. In this study, the Fornell-Larcker criterion was satisfied, as the square root of the AVE for each construct was higher than the inter-construct correlations. This indicates that the constructs namely SCT, RTB, PRT, DMT, and FSCT, measure distinct concepts and are not excessively related, thereby validating the uniqueness of each construct in the model. Cross-loadings were also examined to further verify construct validity. In a well-specified model, items should load higher on their intended constructs than on other constructs. The analysis confirmed that all items had higher loadings on their respective constructs, which ensures that each indicator was more aligned with its associated construct than with others. This cross-loading analysis bolstered the evidence of good discriminant validity, affirming that the constructs are distinct from one another. The results for both reliability and construct validity are presented in **Table 3**.

The results presented in **Table 3** strongly support the construct validity of the measurement model. Construct validity is demonstrated when the indicators used to measure a construct adequately represent the underlying theoretical concept. In this case, convergent validity—a critical aspect of construct validity—is confirmed by several criteria. First, the factor loadings for each item are well above the acceptable threshold of 0.70, indicating that the items are highly correlated with their respective constructs and, therefore, adequately capture the intended theoretical dimensions. Furthermore, the composite reliability values for each construct exceed 0.80, highlighting the internal consistency of the items within each construct. This reinforces the idea that the indicators reliably measure the same underlying construct. Additionally, Cronbach's alpha values for all constructs are above the recommended 0.70 threshold, further confirming the reliability and internal coherence of the measurement model. The average variance extracted (AVE) for each construct is greater than 0.50, indicating that more than 50% of the variance in the items is explained by the construct, which is a key indicator of convergent validity. The combination of high factor loadings, strong composite reliability, and adequate AVE values provides compelling evidence that the constructs exhibit strong convergent validity, thereby supporting the overall construct validity of the model.

6.3.2. Reliability

Reliability was confirmed using Cronbach's alpha, with values ranging between 0.80 and 0.92 for all constructs. Cronbach's alpha values above 0.70 are generally considered acceptable, and values above 0.80 indicate high internal consistency. This means that the items within each construct are highly correlated and measure the same underlying concept, ensuring the reliability of the measurement model. For instance, the Cronbach's alpha for SCT was 0.89, indicating excellent internal consistency. Similarly, RTB and DMT had Cronbach's alpha values of 0.87 and 0.86, respectively, further supporting the robustness of the constructs. Together, the Fornell-Larcker criterion, cross-loadings, and high Cronbach's alpha values confirm that the constructs used in this study are both valid and reliable, providing a strong foundation for the structural model. This ensures that the subsequent analysis of the relationships between blockchain technology practices and food supply chain transparency can be interpreted with confidence.

6.3.3. Convergent validity

Convergent validity was assessed using CR, AVE, and Factor Loadings presented in **Table 2** above. All values exceeded the recommended thresholds, confirming that the constructs exhibited convergent validity. For example, SCT shows a CR of 0.886, Cronbach's Alpha of 0.89, and an AVE of 0.666, indicating high reliability and validity. The factor loadings for individual items, such as SCT1 (0.781) and SCT2 (0.852), also confirm that each item is a good indicator of the construct it measures. These results demonstrate that blockchain-related constructs are measured reliably in this study, with strong internal consistency and clear relevance to their respective constructs. The CR values for other constructs, such as RTB with a CR of 0.884 and an AVE of 0.665, further support the notion that these constructs are well-represented by their respective indicators. The high factor loadings for RTB items also indicate that the items are strongly related to the underlying construct. Similarly, PRT and DMT exhibited CR values of 0.896 and 0.910, respectively, along with high AVE scores (both above 0.68), further affirming the strong convergent validity of the constructs in this study. Moreover, the AVE values, all above the threshold of 0.50, suggest that more than 50% of the variance in the items is explained by their respective latent constructs, which is a critical criterion for establishing convergent validity. This ensures that the measurement model is robust and accurately captures the essence of blockchain practices in the food supply chain. The combination of high CR, AVE, and factor loadings underscores the reliability of the measurement model and confirms that the constructs used in the study are both valid and capable of explaining the relationships in the theoretical framework.

6.4. Fornell-larcker criterion on discriminant validity

Discriminant validity ensures that constructs that are not supposed to be related are distinct from one another. The Fornell-Larcker criterion is commonly used to assess discriminant validity. According to this criterion, the square root of the AVE for each construct should be greater than its correlation with other constructs. The Fornell-Larcker criterion is satisfied, as the square root of AVE for each construct is greater than its correlation with other constructs and results are presented in **Table 4** below.

Table 4. The Fornell-Larcker criterion on discriminant validity.

Construct	AVE	SCT	RTB	PRT	DMT	FSCT
SCT	0.666	0.816				
RTB	0.665	0.60	0.816			
PRT	0.684	0.554	0.504	0.827		
DMT	0.717	0.523	0.481	0.575	0.847	
FSCT	0.708	0.450	0.442	0.465	0.471	0.842

In **Table 4** the AVE column represents the Average Variance Extracted for each construct, indicating the amount of variance that is captured by the construct relative to the variance due to measurement error. In the table, the diagonal values represent the square root of the AVE for each construct, while the off-diagonal values represent correlations between constructs. The square roots of AVE for each construct, for example, 0.816 for SCT and 0.842 for FSCT, are greater than the correlations with other constructs, satisfying the Fornell-Larcker criterion. This indicates that the constructs are distinct from each other and confirms that discriminant validity is established, meaning each construct is distinct and measures a unique concept within the model. The square root of the AVE for each construct is greater than its correlations with other constructs, ensuring discriminant validity. For instance, the square root of AVE for SCT is 0.816, and its correlation with RTB is 0.60, satisfying the Fornell-Larcker criterion. This indicates that the constructs, while related, measure distinct aspects of blockchain adoption, which is essential for the integrity of the model

6.5. Goodness of fit assessment results for the measurement model

To evaluate the goodness of fit for the measurement model, several fit indices were analyzed. These include the Standardized Root Mean Square Residual (SRMR), Chi-square (χ^2), Comparative Fit Index (CFI), and the Root Mean Square Error of Approximation (RMSEA). These indices are critical in determining how well the hypothesized model fits the observed data.

According to the results in **Table 5**, the factor loadings for the items measuring Smart Contracting (SCT1-SCT4) range from 0.781 to 0.852, indicating strong item reliability. Composite Reliability (CR) values are high for all constructs, such as 0.886 for SCT and 0.910 for DMT. Cronbach's Alpha values, such as 0.89 for SCT and 0.86 for DMT, also confirm internal consistency. The Average Variance Extracted (AVE) values, such as 0.666 for SCT and 0.717 for DMT, indicate that more than 66% of the variance in the constructs is captured by the items, ensuring good convergent validity The SRMR value of 0.05 is below the threshold of 0.08, indicating a good fit between the model and the data. The CFI of 0.94 is above the recommended value of 0.90, signifying an excellent model fit. Additionally, the RMSEA of 0.04 is well below the 0.06 threshold, further confirming the excellent fit of the measurement model. The goodness of fit indices (SRMR = 0.05, CFI = 0.94, RMSEA = 0.04) confirm that the measurement model is robust, and the high R^2 value of 0.64 indicates that blockchain practices are crucial determinants of supply chain transparency. These findings underscore the potential of blockchain technology to enhance trust, traceability, and accountability in South Africa's food sector. Thus, other fit indices like SRMR, CFI, and RMSEA are considered more reliable in determining the goodness of fit. Overall, the goodness of fit indices demonstrates that the measurement model is well-specified and exhibits a good fit with the data. This suggests that the measurement model effectively captures the relationships among SCT, TRB, PRT, DMT, and FSCT.

Table 5. Goodness of fit assessment results for the measurement model.

Fit Index	Recommended threshold	Model value	Interpretation
Standardized root mean square residual (SRMR)	<0.08	0.05	Good fit
Comparative fit index (CFI)	>0.90	0.94	Excellent fit
Root mean square error of approximation (RMSEA)	<0.06	0.04	Excellent fit

6.6. Structural model validation results

The structural model tested the relationships between the independent variables and the dependent variable FSCT. The model validation was performed using PLS-SEM, incorporating the variables SCT, TRB, PRT, DMT, and the dependent variable FSCT.

Table 6 shows that the SRMR value of 0.05, which is well below the 0.08 threshold, confirms a good model fit, indicating that the measurement and structural models align well with the data. The R^2 value of 0.64 shows that the four independent variables SCT, RTB, PRT, and DMT, explain 64% of the variation in FSCT. This high explanatory power suggests that these blockchain-related practices play a critical role in enhancing transparency within the food supply chain. The findings highlight the importance of these variables in ensuring that supply chain processes are more visible, efficient, and trustworthy. As such, the adoption of blockchain-enabled systems like smart contracts, traceability mechanisms, tracking, and monitoring solutions can significantly improve transparency, which is crucial for regulatory compliance and stakeholder trust.

Table 6. Model validation results.

Dependent variable	Independent variables	SRMR	R^2	Interpretation
Food Supply Chain Transparency (FSCT)	Smart Contracting (SCT), Records Traceability (RTB), Production Tracking (PRT), Distribution Monitoring (DMT)	0.05	0.64	Good fit and high explanatory power

6.7. PLS results on hypotheses testing

The hypotheses were tested using bootstrapping in the PLS-SEM analysis. All hypotheses were supported, indicating significant positive relationships between the independent variables and FSCT.

Table 7. Path coefficients and hypothesis testing results.

Hypothesis	Path coefficient	*t*-value	*p*-value	Decision
H1: SCT → FSCT	0.42	7.83	<0.001	Supported
H2: RTB → FSCT	0.39	6.95	<0.001	Supported
H3: PRT → FSCT	0.35	6.12	<0.001	Supported
H4: DMT → FSCT	0.37	6.56	<0.001	Supported

The results in **Table 7** show that all hypotheses are supported, with path coefficients showing significant positive relationships between blockchain practices and FSCT. For example, the relationship between SCT and FSCT has a path coefficient of 0.42 and a *t*-value of 7.83 ($p < 0.001$), indicating that smart contracts have the strongest influence on transparency. This strong impact can be attributed to the ability of smart contracts to automate agreements and enforce rules without the need for intermediaries, ensuring that transactions within the supply chain are transparent, secure, and auditable. The automatic execution of contracts minimizes human error and fraud, which is crucial in the food supply chain, where transparency and trust are paramount for safety and quality assurance (Zheng et al., 2020). RTB has a path coefficient of 0.39, highlighting the critical role of traceability systems in enhancing visibility across the supply chain. Tian (2016) and Pearson et al. (2019) emphasize that traceability enhances consumer trust, as customers can verify the authenticity and safety of the products they purchase. PRT, with a coefficient of 0.35, plays a significant role in ensuring that production processes comply with safety and quality standards. Blockchain's ability to record production data in real-time allows for continuous monitoring and verification of compliance with regulatory standards, reducing risks related to food safety. This finding is consistent with the argument of Feng et al. (2020), who suggest that blockchain can improve operational efficiency by eliminating manual checks and offering real-time insights into production activities. DMT, with a path coefficient of 0.37, confirms the importance of tracking food transportation and storage conditions to maintain product quality. The results show that SCT, TRB, PRT, and DMT significantly influence FSCT. SCT had the strongest impact, highlighting its role in automating transactions and improving trust within the supply chain.

7. Findings and discussions

This finding aligns with Zheng et al. (2020), who emphasize that smart contracts enhance transparency by automating compliance and reducing human intervention in transaction processes, thereby increasing trust among supply chain actors. Blockchain ensures that critical data such as temperature, humidity, and handling conditions are logged in real-time and cannot be tampered with. This is especially crucial for perishable goods, where any deviation from the required conditions can lead to spoilage or safety risks. Saberi et al. (2019) highlight that blockchain-based distribution monitoring improves not only transparency but also the efficiency of logistics operations by ensuring that food products arrive at their destination in optimal conditions. Additionally, Pearson et al. (2019) concur that smart contracts provide a tamper-proof and automated method for enforcing agreements, making it easier for companies to maintain transparent and accountable relationships within their supply chains. RTB and DMT also had substantial effects, reinforcing the importance of tracking food products across the supply chain. The significance of traceability is consistent with the work of Tian (2016), who argued that blockchain-based traceability systems can greatly reduce the risk of food fraud and contamination by providing a secure and verifiable history of food products. Moreover, Saberi et al. (2019) support the finding on distribution monitoring, stating that real-time tracking of food transportation conditions, such as temperature and location, is crucial for ensuring that products meet quality standards and regulatory requirements.

On the other hand, some studies offer a more critical perspective. For instance, Kshetri (2018) suggests that while blockchain-based traceability systems offer substantial benefits, they may be difficult to implement for small and medium enterprises (SMEs) due to technical complexity and high costs. Similarly, Treiblmaier (2018) notes that the integration of blockchain in supply chains is still in its infancy, and many companies face challenges related to scalability and interoperability, which can limit the effectiveness of solutions like smart contracts and distribution monitoring. In the context of blockchain technology for the agri-food supply chain, scalability refers to the system's ability to efficiently handle increasing transaction volumes as the supply chain grows, while interoperability ensures seamless data exchange across different platforms and stakeholders to maintain transparency and traceability (Johnson et al., 2023; Xu and Li, 2023). Despite these challenges, the consensus in the literature agrees with the study's findings, as blockchain technology has been widely recognized for its potential to improve transparency, traceability, and accountability in the food supply chain. PRT, which contributed significantly to transparency by ensuring that processes meet safety and quality standards, echoes the conclusions of Feng et al. (2020), who highlight that blockchain can enhance the monitoring of production processes to ensure compliance with safety standards, thus minimizing risks related to food safety and quality. The study's strengths include its use of recent literature and its comprehensive coverage of blockchain applications across diverse domains, offering practical insights into real-world implementations. However, it is limited by a reliance on secondary data and lacks in-depth analysis of technical challenges and regulatory issues that could affect blockchain adoption.

8. Conclusion

This study demonstrated that blockchain adoption, particularly through smart contracting, records traceability, production tracking, and distribution monitoring, enhances transparency in the food supply chain among South African SMEs. The findings provide valuable insights for both policymakers and practitioners, showcasing how blockchain technology can improve transparency, trust, operational efficiency, and regulatory compliance in the food industry. These results suggest that blockchain not only addresses transparency issues but also provides a foundation for enhanced collaboration among supply chain participants by creating a shared, immutable ledger of transactions. The positive and significant relationships between these blockchain-enabled practices and FSCT reinforce the argument that blockchain technology is a powerful tool for enhancing transparency, accountability, and trust in the food supply chain. By improving data accuracy, reducing fraud, and facilitating real-time monitoring, blockchain contributes to a more resilient and efficient food system, which is essential for meeting regulatory requirements and maintaining consumer confidence. For policymakers, the study underscores the importance of fostering an enabling regulatory environment that encourages the adoption of blockchain solutions, particularly for SMEs that might otherwise struggle with issues like food fraud and inefficient supply chains. Practitioners, on the other hand, can leverage blockchain technology to ensure traceability, prevent counterfeiting, and mitigate risks associated with non-compliance with food safety standards. Moreover, blockchain adoption aligns with global trends toward sustainable supply chains, as noted by Saberi et al. (2019), who argue that blockchain can promote more ethical sourcing and reduce environmental impacts through better visibility across the supply chain. In an increasingly transparent and regulated global market, SMEs adopting blockchain can enhance their reputation by demonstrating a commitment to food safety and quality, which in turn can increase consumer confidence and loyalty. Additionally, as shown by Feng et al. (2020), blockchain-enabled systems allow for real-time tracking and data analytics, further improving decision-making and reducing inefficiencies. Thus, by adopting blockchain technologies, SMEs in South Africa can gain a competitive advantage not only domestically but also in international markets that prioritize transparency and sustainability.

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