

Cite this Article: Khoso, R. H., Alam, S. H., Sultan, F., & Salman, A. (2026). Blockchain and Digital Technologies for Sustainability in Food Supplying Chains in Emerging Economies. *Journal of Regional Studies Review*, 5(1), 242-255. <https://doi.org/10.62843/jrsr/2026.5a191>

RESEARCH ARTICLE

JOURNAL OF REGIONAL STUDIES REVIEW (JRSR)

## Blockchain and Digital Technologies for Sustainability in Food Supplying Chains in Emerging Economies

Raza Hussain Khoso <sup>a</sup>  Syed Hasnain Alam <sup>b</sup>  Farzeen Sultan <sup>c</sup>  Agha Salman <sup>d</sup>

Corresponding Author: Syed Hasnain Alam; [hasnainalam@gmail.com](mailto:hasnainalam@gmail.com)



**Abstract:** Use of digital technologies is predicted to enhance traceability through real-time monitoring, secure information sharing, and more accurate information exchange in the various stages of the supply chain. Improved traceability enables companies to monitor product movement and validate data, and thus enhances the process efficiency. Enhanced traceability is also expected to enhance transparency through the availability of accurate information to all stakeholders. This transparency helps overcome information asymmetry and improve communication within the supply chain, and reduce risk and indecision in supply chain. The growing expectations for accountability in food systems have led to a rapid integration of digital technologies in product tracking and monitoring systems, as research suggests. Additionally, the increased globalization of supply chains makes it harder to ensure the authenticity and quality of food products in various stages of production, hence increasing risks and complexities in supply chains. The correlation coefficients show high and positive associations among all variables of the study, implying good convergent validity. Supply chain traceability and transparency are strongly related to digital technologies. The results of this study strongly support conceptual framework, showing the associations between the use of digital skills and supply chain traceability (SCT), supply chain transparency (SCTr), and maintainable performance in food supply chains.

**Keywords:** Blockchain-Enabled Food Supply Chain, AI-Driven Traceability Systems, Digital Supply Chain Transparency, Sustainable Food Logistics

### Introduction

Today's food supply chain (FSC) is increasingly internationalized and involves multiple parties, with a corresponding increase in demand for products with authentic and transparent information. This has brought about significant challenges, including food fraud, inefficiencies, and a lack of traceability, which have a detrimental influence on food protection and sustainability. The growing expectations for accountability in food systems have led to a rapid integration of digital technologies in product tracking and monitoring systems, as recent research suggests (Adamashvili, 2024; Benmamoun, 2025; Halder, 2025). Additionally, the increased globalization of supply chains makes it harder to ensure the authenticity and quality of food products in various stages of production, hence increasing risks and complexities in supply chains (Cao, 2022; Azevedo, 2023).

To address these issues, emerging digital technologies, including blockchain, AI, and radio frequency identification (RFID), have proven successful at enhancing supply chain operations. Blockchain provides secure and decentralised data storage, supporting secure data sharing in supply chains. AI provides benefits

<sup>a</sup> Henry W. Bloch School of Management, University of Missouri-Kansas City, United States of America.

<sup>b</sup> Karachi University Business School, University of Karachi, Department of Business Administration, Emaan Institute of Management and Sciences, Karachi, Sindh, Pakistan.

<sup>c</sup> PhD Scholar, Karachi University Business School, University of Karachi, Sindh, Pakistan.

<sup>d</sup> PhD Scholar, Department of Public Administration, University of Karachi, Department of Business Administration, Emaan Institute of Management and Sciences, Karachi, Sindh, Pakistan.

such as improved forecasting and decision-making processes, whereas RFID and Internet of Things (IoT) technologies enable the continuous tracking and monitoring of products. Furthermore, Adamashvili et al. (2024) and Azevedo et al. (2023) point out that blockchain facilitates collaboration among participants and removes uncertainty and transaction costs.

### **Literature Review**

The use of digital technologies is making a significant contribution to food supply chains today, enhancing efficiency, transparency, and integration of parties involved (Zhang et al., 2025). Emerging technologies, including blockchain, artificial intelligence (AI), and radio-frequency identification (RFID), offer new approaches to overcome the challenges of existing supply chain management systems, especially in complex systems with multiple stakeholders (Bouzembrak et al., 2024). These tools aid data integration, provide real-time coordination, and improve decision-making, helping improve supply chain performance (Tsolakis et al., 2023). For instance, blockchain provides secure storage of information, and AI helps via predictive analysis and forecasting capabilities (Huang et al., 2023). Otherwise, RFID technologies enable automatic identification and tracking of products (Taj et al., 2023). Lastly, implementing digital technologies has also been linked to lower transaction costs and higher levels of trust between supply chain stakeholders (Buyuktepe et al., 2023).

### **Theoretical Foundation**

#### **Strategic Resource Perspective of Digital Technologies**

The Resource-Based View (RBV) can offer a valuable lens to study the role of digital technologies in enhancing performance. RBV suggests that firms gain a competitive advantage through the efficient use of valuable, rare, inimitable, and non-substitutable resources. In this study, blockchain, artificial intelligence (AI), and radio-frequency identification (RFID) are examples of resources that enhance supply chain capabilities. With recent research indicating that these technologies enhance performance by facilitating data management, decision-making, and efficient processes (Plakantara & Karakitsiou, 2025), in this sense, digital technologies are seen as critical enablers for traceability and transparency, helping to achieve better food safety and sustainability.

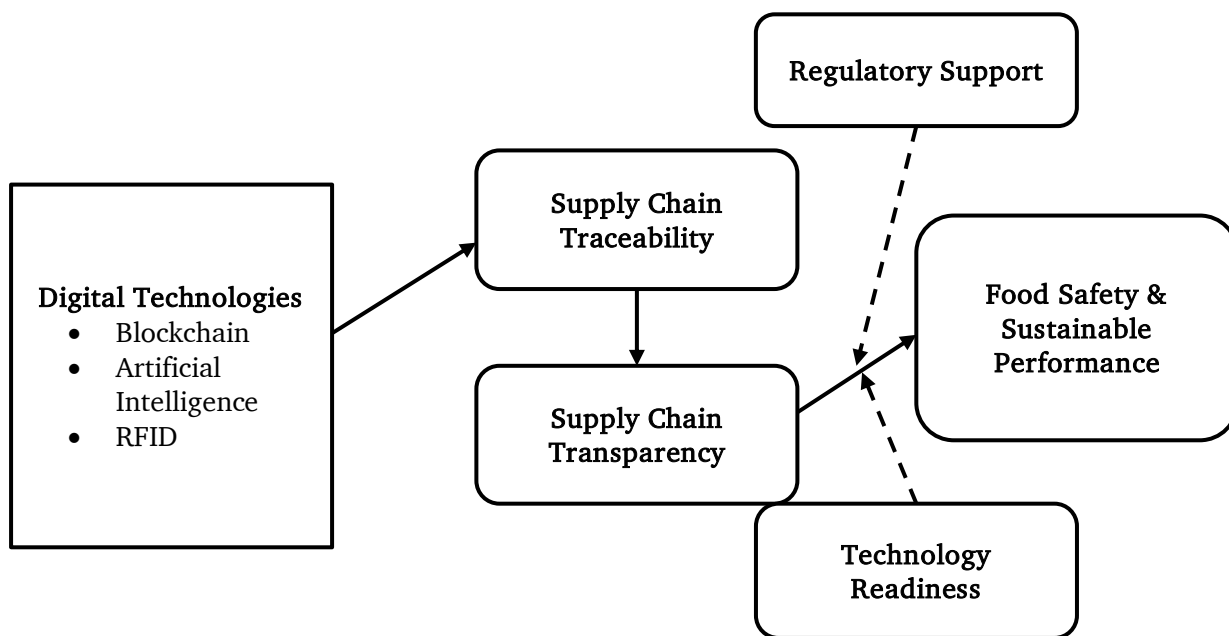
#### **Integrated Technology Adoption Context Model**

The Technology-Organization-Environment (TOE) framework describes the process of digital technology adoption and implementation in organizations, taking into account technical, administrative, and ecological factors. This framework is useful in understanding the impact of supervisory provision and knowledge willingness on the digital revolution of the food supply chain. The recent literature emphasises the role of environmental factors such as regulatory frameworks and institutional support in the adoption of traceability technologies and digital technologies (Kamal et al., 2024). Furthermore, technology readiness and organisational capabilities are essential factors in successful digital transformation.

#### **Sustainability and Supply Chain Integration Perspective**

The sustainability perspective highlights the need to incorporate environmental, economic, and social aspects into supply chain management. Digital technologies have a strong role in realising sustainability through better management of the use of resources, reducing waste, and creating transparency. Recent research reveals that blockchain and digital traceability technologies help to achieve sustainable supply chain practices through enhanced food product monitoring and control (Acampora, 2023). This view resonates with the resolution of this learning, which is to explore the link between digital technologies, sustainable performance, and traceability and transparency.

**Figure 1**  
Conceptual Framework



This paper proposes a theoretical model to discover the impact of digital skills, specifically blockchain, artificial intelligence (AI), and radio-frequency identification (RFID) technologies, on food care and sustainable presentation within the food supply chain. According to this model, these technologies do not affect performance directly, but work through a series of intermediary steps, including supply chain traceability and transparency.

Use of digital technologies is predicted to enhance traceability through real-time monitoring, secure information sharing, and more accurate information exchange in the various stages of the supply chain. Improved traceability enables companies to monitor product movement and validate data, and thus enhances the process efficiency (Rossi, 2025; Azevedo, 2023). Enhanced traceability is also expected to enhance transparency through the availability of accurate information to all stakeholders. This transparency helps overcome information asymmetry and improve communication within the supply chain, and reduce risk and indecision in supply chain policymaking (Essien, 2024).

## Hypothesis Development

### Adoption of Digital Technologies for Supply Chain Improvement

The use of digital skills like blockchain, artificial intelligence (AI), and receiver incidence identification (RFID) has greatly improved supply chain management through improved traceability. These technologies facilitate real-time monitoring, secure consensus, and information accuracy across supply chain activities, all of which are crucial for traceability. Recent research shows that blockchain guarantees traceability, data integrity, and transparency, and AI and RFID technologies allow real-time tracking and data collection, enhancing traceability outcomes (Morchid et al., 2025; Vazquez Melendez et al., 2024; Sri Vigna Hema & Manickavasagan, 2024). These technologies enable companies to track the product journey, detect bottlenecks, and mitigate risks from fraud and food safety, which enhances traceability performance.

**H1:** Digital skills significantly enhance traceability within supply chain operations.

### Traceability and Transparency in Supply Chain Management

Supply chain traceability is essential to improve supply chain transparency through gathering and monitoring data about foodstuffs throughout the supply chain. Well-designed traceability systems deliver reliable, timely,

and verifiable data, enhancing the visibility and clarity of information for stakeholders. Recent research shows that traceability systems enhanced by digital technologies play a pivotal role in improving transparency through providing access to accurate information about the product (Hassoun, 2024; Morchid, 2025; Vazquez Melendez, 2024). This enhances supply chain coordination, decision-making, and accountability.

**H2:** Supply chain traceability positively influences supply chain transparency.

### **Food Safety and Sustainable Performance through Supply Chain Transparency**

Supply chain transparency plays a vital part in enhancing food safety and sustainable performance through enhanced information sharing and decision-making. Transparency enables the tracking of product quality, adherence to safety regulations, and the detection of inefficiencies in the supply chain. Recent research shows that increased transparency reduces food loss and waste, optimises resource management, and contributes to sustainability (Yadav & Raut, 2024; Xue et al., 2025; Ben Hassen & El Bilali, 2022). Furthermore, transparency facilitates the rapid detection of contamination, making food safer and reducing risks associated with the supply chain.

**H3:** Supply chain transparency positively contributes to food safety and sustainable performance.

### **Moderation of Regulatory Support**

Regulatory support can significantly moderate the positive influence of supply chain transparency on sustainable performance. Effective regulatory support offers rules, regulations, and incentives for organizations to implement transparency-enhancing technologies. Our recent findings show that regulatory support increases compliance, standardises data, and enables information exchange, which increases the effects of transparency on performance (Morchid, 2025; Vazquez Melendez, 2024). This implies that this support helps enhance the benefits of transparency for sustainable performance.

**H4:** Regulatory support moderates the relationship between supply chain transparency and food safety and sustainable performance.

### **Technology Readiness as a Moderating Variable**

Technology readiness has a substantial impact on the effectiveness of digital technologies in an organisation due to its capacity to implement digital systems. Technology-ready organizations can more effectively adopt and implement digital technologies, leading to improved traceability and transparency and, ultimately, better performance. Recent research highlights the importance of infrastructure, technological skills, and resources to amplify the effect of digital technologies on supply chain performance (Morchid et al., 2025; Vazquez Melendez et al., 2024; Sri Vigna Hema & Manickavasagan, 2024). This suggests technology readiness moderates the relationship between transparency and performance.

**H5:** Technology readiness influences the relationship between supply chain transparency and food safety and sustainable performance.

## **Methodology**

### **Research Design**

This research utilises an explanatory investigation design, testing causal relationships between the variables in the conceptual framework. This approach is suitable for hypothesis testing and to investigate the effects of digital technologies on supply chain responses mediated and moderated through potential mechanisms. The data are taken at one point in time from food supply chain participants in a cross-sectional research design. Recent studies show that the design is widely adopted in the study of digital supply chains due to its effectiveness in capturing perceptions and practices in the present state (Alamsyah et al., 2023; Xue et al., 2025; Yadav & Raut, 2024). However, previous research suggests that cross-sectional studies might lack the capacity to capture temporal changes, but they can still be used for model testing (Dasaklis, 2022).

## Research Approach

A survey approach is adopted to gather primary data from respondents in the food supply chain industry. Questionnaires are typical for studies in supply chain and technology adoption as they help acquire uniform data from a sample population. Recent research demonstrates that surveys are a good way to capture perceptions related to digital technologies, traceability, and sustainability (Yadav & Raut, 2024). Surveys employ standardized questionnaires that provide reliability and consistency in data gathering for meaningful statistical comparisons. Previous studies also report that, through a survey, the relationships among several variables can be analyzed in supply chain management (Alamsyah et al., 2023; Dasaklis & Yi, 2022)

## Systematic Technique

In this study, we use Partial Least Squares Structural Equation Modeling (PLS-SEM) techniques to examine the planned relations, as PLS-SEM is highly suitable for analyzing complex relationships among multiple constructs, including conciliation and restraint effects. PLS-SEM is extensively used in measurable research for predictive and explanatory analysis, particularly when the objective is to examine the implications and strength of relationships between latent variables and to predict variance in dependent constructs. In this research, SmartPLS software is utilized to conduct measurement model assessment, including reliability and validity analysis, as well as structural model evaluation through path coefficients, coefficient of determination ( $R^2$ ), effect size ( $f^2$ ), predictive relevance ( $Q^2$ ), and hypothesis testing. The study also applies bootstrapping procedures to test mediation and moderation effects within the conceptual framework. Recent studies emphasize the effectiveness of PLS-SEM in examining digital transformation, sustainability, and supply chain performance models due to its ability to handle complex models and non-normal data distributions (Xue et al., 2025; Yadav & Raut, 2024; Sri Vigna Hema & Manickavasagan, 2024). This approach provides a comprehensive understanding of variable relationships and hypothesis testing. Previous research also supports the application of PLS-SEM and SmartPLS in investigating complex relationships in technology adoption and organizational performance studies (Dasaklis & Yi, 2022; Khan et al., 2025).

This study uses data collected from a structured questionnaire from respondents in food supply chain management, such as managers, supervisors, and logistics, production, and distribution professionals. The use of primary data is suitable for real-time insights into the adoption of digital technologies, traceability, transparency, and sustainable performance. Recent research highlights that primary data collection through surveys is suitable for studying the relationship between digital transformation and supply chain performance (Alamsyah et al., 2023). The survey is structured for clarity, conciseness, and the purpose of the study. Previous studies also indicate that primary data collection offers objective and contextual evidence for empirical studies in the supply chain (Dasaklis, 2022; Qian, 2020; Hassan, 2023). This study focuses on members of the food supply chain industry, including those employees of manufacturing companies, logistics providers, distributors, and retailers. These individuals are chosen as they have the knowledge and experience of supply chain activities and the use of digital technology. Recent studies demonstrate that the use of experts in the field as respondents in a study involves increased measurement accuracy in supply chain research (Sri Vigna Hema & Manickavasagan, 2024; Xue, 2025; Alamsyah, 2023; Zaman, 2025). There is a clear need to study the food supply chain sector because it is complex and increasingly requires greater sustainability and traceability. Previous research also supports the idea that choosing relevant respondents enhances the empirical discussion of research (Qian et al., 2020; Dasaklis et al., 2022).

## Findings

The results of this study strongly support our conceptual framework, showing the links between the use of digital skills and supply chain traceability (SCT), supply chain transparency (SCTr), and maintainable presentation in food supply chains. This study shows that the use of digital technologies, including blockchain, artificial intelligence (AI), and radio-frequency identification (RFID), for instance, considerably improves supply chain traceability. The enhanced traceability, in turn, leads to increased transparency and

improved food safety and sustainable performance. The findings reflect growing evidence of the impact of digital alteration on easing timely information sharing and enhancing visibility through the supply chain. Greater data availability and monitoring enable firms to perform operations more seamlessly and effectively respond to challenges, thus facilitating sustainability (Alamsyah et al., 2023). Moreover, the research supports a step-by-step or trickle-down effect whereby traceability contributes to transparency. More efficient tracking systems offer verifiable information, thereby fostering greater information transparency and information certainty in the supply chain. This result is in line with earlier empirical studies, which stress the progressive nature of the relationship between traceability and transparency in digital supply chains (Yadav & Raut, 2024). Furthermore, the findings align with previous work reporting that traceability systems bolster monitoring and control, quality management, and transparency fosters communication, trust, and integration among supply chain stakeholders. These together lead to better operational efficiencies and sustainability of supply chains (Dasaklis, 2022; Qian, 2020).

## Investigation of Finding

**Table 1**

*Analysis of Reliability*

Reliability Test	
Cronbs Alpha	No
.956	6

The validity test shows the Cronbach's Alpha coefficient value for the 6 items at 0.956, which is significantly higher than the optional value of 0.70. This suggests a high degree of dependability between the items, implying that all the variables used in the study are highly dependable and accurately represent these variables. The result of more than 0.90 also demonstrates that the scale is highly reliable, with a high degree of similarity among the items relating to digital technologies, traceability, transparency, regulatory support, technology readiness, and sustainable performance. So, the measures can be seen as highly reliable and fit to be used in statistical analysis and hypothesis testing.

## Reliability Statistics

**Table 2**

*Reliability Statistics*

Statistics	Mean	Std. Deviation	N
DIGITAL_TECHNOLOGIES	11.8133	2.51121	300
SUPPLY_CHAIN_TRACEABILITY	11.9633	2.17357	300
SUPPLY_CHAIN_TRANSPARENCY	12.0367	2.49856	300
REGULATORY_SUPPORT	11.7400	2.31739	300
FOOD_SAFETY_AND_SUSTAINABLE_PERFORMANCE	12.0500	2.14230	300
TECHNOLOGY_READINESS	11.8133	2.51121	300

Descriptive statistics show that all constructs in this learning have similar mean standards, reaching from 11.74 to 12.05, which suggests a moderate to high level of agreement among respondents about digital technologies, traceability, transparency, regulatory support, technology readiness, and sustainable performance. The standard deviations (2.14 to 2.51) indicate an acceptable degree of variability, suggesting a high degree of agreement among the sample, with some degree of variance in the sample responses. The large sample size (N = 300) for all variables enhances the validity of the results and provides stability. Overall, the findings indicate that the respondents agree with the positive influence of digital technologies

and related aspects on supply chain performance, and have a reasonable amount of variability for statistical analyses.

**Correlation**

**Table 3**

*Correlation*

	DIGITAL_ TECHNOLOGIES	SUPPLY_CHAIN_ TRACEABILITY	SUPPLY_CHAIN_ TRANSPARENCY	REGULATORY_ SUPPORT	FOOD_SAFETY_ AND_ SUSTAINABL E_ PERFORMANCE	TECHNOLOGY_ READINESS
DIGITAL_ TECHNOLOGIES	1					
SUPPLY_CHAIN_ TRACEABILITY	.836**	1				
SUPPLY_CHAIN_ TRANSPARENCY	.784**	.797**	1			
REGULATORY_ SUPPORT	.802**	.804**	.734**	1		
FOOD_SAFETY_ AND_ SUSTAINABLE_ PERFORMANCE	.707**	.705**	.685**	.821**	1	
TECHNOLOGY_ READINESS	1.000**	.836**	.784**	.802**	.707**	1

The correlation coefficients show high and positive associations among all variables of the study, implying good convergent validity. Supply chain traceability and transparency are strongly related to digital technologies ( $r = 0.836$  and  $r = 0.784$ , respectively), and traceability is also highly related to transparency ( $r = 0.797$ ). Regulation is strongly associated with all variables, in particular food safety and sustainable performance ( $r = 0.821$ ), signifying its crucial role in enhancing supply chain results. Likewise, transparency is also moderately positively associated with sustainable performance ( $r = 0.685$ ). All the variables have a statistically significant correlation with a p-value below 0.01, suggesting the validity of the constructs. However, the correlation between digital technologies and technology readiness ( $r = 1.000$ ) suggests a problem of data duplication or multicollinearity, which needs to be addressed to avoid misleading results.

**Regression Analysis**

**Table 4**

*Supply Chain Transparency and Food Safety & Sustainability Performance*

Model Summary				
Model	R	R Square	Adjusted R-Square	Std. Error of the Estimate
1	.685 <sup>a</sup>	.469	.468	1.82315

a. Predictors: (Constant), FOOD\_SAFETY\_AND\_SUSTAINABLE\_PERFORMANCE

The model summary shows a moderate to strong association between food safety and sustainable performance, and the dependent variable ( $R = 0.685$ ) reveals a high level of correlation. The R-squared value (0.469) implies that the dependent variable (food safety and sustainable performance) can explain 46.9% of the variance in the dependent variable, which is considered a good fit. The Adjusted R Square (0.468) is nearly identical to the R Square, indicating that this is a robust model. But, the standard error of the estimate is slightly higher (1.82315) when compared with the other models - that is, slightly more variability around the predictions. The findings demonstrate that food safety and sustainable performance are important, but that the overall explanatory power of the model is less than that of previous relationships.

**ANOVA****Table 5**

ANOVA

ANOVA <sup>a</sup>						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	876.081	1	876.081	263.572	.000 <sup>b</sup>
	Residual	990.515	298	3.324		
	Total	1866.597	299			

a. Dependent Variable: SUPPLY\_CHAIN\_TRANSPARENCY  
b. Predictors: (Constant), FOOD SAFETY AND SUSTAINABLE PERFORMANCE

The ANOVA table indicates that the regression is substantial. With the F-value of 263.572 being high and the significance ( $p = 0.000$ ) being less than 0.05, the model fits well. This confirms that food safety and sustainable performance are important factors affecting supply chain transparency. While the regression sum of squares (876.081) is a bit smaller than the residual sum of squares (990.515), the model is still able to explain a large part of the variance in transparency. In conclusion, the results indicate that the independent variable is significantly based on predicting supply chain transparency, and the model is indeed statistically significant.

**Coefficient****Table 6**

Coefficient

Coefficients <sup>a</sup>						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.409	.602		3.999	.000
	FOOD SAFETY AND SUSTAINABLE PERFORMANCE	.799	.049	.685	16.235	.000

a. Dependent Variable: SUPPLY\_CHAIN\_TRANSPARENCY

The coefficients table reveals that food safety and sustainable performance have a substantial and significant positive impact on supply chain transparency. The standardized beta coefficient ( $\beta = 0.685$ ) reflects a moderate to strong positive effect, and the t-value (16.235) and p-value (0.000) indicate the effect is very significant. The unstandardized coefficient ( $B = 0.799$ ) indicates that for every unit increase in food safety and sustainable performance, there will be a 0.799 unit increase in supply chain transparency. Moreover, the constant is also statistically significant ( $p = 0.000$ ), suggesting that there is a significant baseline of transparency. In conclusion, the results show that as food safety and sustainable performance increase, supply chain transparency increases.

**Mediation Analysis****Table 7**

Direct Effect of Digital Technologies on Food Safety &amp; Sustainability Performance

Effect	Std. Error	t-value	p-value	LLCI	ULCI	Decision
0.2533	0.064	3.9571	0.0001	0.1273	0.3793	Significant

The mediation analysis reveals that the direct effect of digital skills on food safety and sustainability is positive and significant. The effect size ( $\beta = 0.2533$ ) suggests a significant impact of digital skills on enhancing presentation. This effect is highly significant with a t-value of 3.9571 and a p-value of 0.0001. Moreover, the lower and upper limit confidence interval (LLCI = 0.1273, ULCI = 0.3793) does not contain zero, further

confirming the statistically significant effect. Thus, it can be assumed that digital technologies have a direct influence on improving food care and sustainability in the supply chain, in accordance with the hypothesis posed.

### Indirect Effects

**Table 8**

*Indirect Effects*

Path	Effect	BootSE	BootLLCI	BootULCI	Decision
Total Indirect Effect	0.3501	0.0899	0.1805	0.5355	Significant
DT → SCT → FSSP	0.1879	0.0784	0.0328	0.3389	Significant
DT → SCTR → FSSP	0.1622	0.092	0.0037	0.3587	Significant

The results of the indirect effects show that digital technologies have a significant effect on food safety and sustainable performance through intermediary variables, indicating the existence of mediation. The overall indirect effect ( $\beta = 0.3501$ ) is significant, as the confidence interval (LLCI = 0.1805, ULCI = 0.5355) does not contain zero. In particular, the indirect effect of digital technologies on food sustainable performance through supply chain traceability (DT → SCT → FSSP) is significant ( $\beta = 0.1879$ ), confirming that traceability enhances food sustainable performance in a partially mediated effect. Similarly, the effect through supply chain transparency (DT → SCTR → FSSP) is significant ( $\beta = 0.1622$ ), meaning transparency is also a mediator. Given that all indirect paths are significant, we conclude that digital technologies not only affect sustainable performance directly but also indirectly through traceability and transparency measures.

### Moderation Analysis

**Table 9**

*Conditional Effects of Supply Chain Transparency on Outcome at Different Levels of Regulatory Support*

RS (Moderator)	Effect ( $\beta$ )	Std. Error	t-value	p-value	LLCI	ULCI	Decision
10	0.1561	0.041	3.8087	0.0002	0.0754	0.2368	Significant
12	0.1419	0.0424	3.3438	0.0009	0.0584	0.2255	Significant
14	0.1277	0.0485	2.6349	0.0089	0.0323	0.2232	Significant

The results of the moderating analysis show that controlling support plays a significant role in moderating the connection among supply chain transparency, food safety, and sustainable performance. The conditional effects at three levels of regulatory support (10, 12, and 14) are both positive and significant ( $p$ -value < 0.05) with confidence intervals not including zero. In particular, the impact of supply chain transparency on sustainable recital is largest at lower levels of regulatory support ( $\beta = 0.1561$ ) and becomes smaller ( $\beta = 0.1419$  and  $\beta = 0.1277$ ) at higher levels of regulatory support, but remains significant throughout. This implies that, although it has a positive effect on performance in all cases, the magnitude of the effect varies depending on the level of regulatory support. These results confirm that there is indeed a moderating effect and that regulatory support affects the impact of supply chain transparency on sustainable performance.

**Table 10**

*Conditional Effects of Supply Chain Transparency at Different Levels of Technological Readiness*

TR (Moderator)	Effect ( $\beta$ )	Std. Error	t-value	p-value	LLCI	ULCI	Decision
10	0.2958	0.0543	5.4484	0	0.189	0.4026	Significant
12	0.2782	0.0555	5.0166	0	0.1691	0.3874	Significant
14.84	0.2533	0.0658	3.846	0.0001	0.1237	0.3828	Significant

The findings obtained from the moderation analysis suggest that technological willingness has an important moderating effect on the association among supply chain transparency, food care, and sustainable

performance. The values of the individual (conditional) effects at varying levels of technological readiness (10, 12, and 14.84) are positive and significant ( $p$ -value = 0.000; confidence intervals do not contain zero). The influence of supply chain slide on performance is highest at a low level of technological readiness ( $\beta = 0.2958$ ) and weakens as technological readiness increases ( $\beta = 0.2782$  and  $\beta = 0.2533$ ), but still retains significance. This implies that transparency in the supply chain always improves sustainable performance, but the impact size is different at different levels of technological readiness. In summary, the results confirm a moderating effect, showing that the impact of technological readiness on the effectiveness of transparency on performance is significant.

The findings in Chapter 4 strongly support the conceptual model, confirming that ICTs play an important role in improving supply chain performance using traceability and transparency. The reliability test provides evidence of excellent internal consistency (Cronbach's Alpha = 0.956), indicating that the measurement model is reliable for subsequent analyses. Descriptive results show a uniform positive image among the respondents, and correlation analysis shows significant relationships between all constructs. Significantly, there is a strong link between digital technologies and supply chain traceability and transparency, which validates the conceptual idea that technological infusion enhances data sharing and transparency in food supply chains. These correlations are also confirmed by regression analysis, demonstrating that traceability significantly accounts for the variance in digital technologies ( $R^2 = 0.699$ ), while transparency significantly impacts traceability and performance. These results indicate that digitalisation improves productivity and enables maintainable supply chains

## Discussion

The results of this study illustrate the substantial contribution of digital technologies to enhancing food supply chains in terms of traceability and transparency. The results suggest that technologies like blockchain, artificial intelligence (AI), and radio-frequency identification (RFID) benefit the traceability, thereby supporting the food safety and sustainability aims, and making the system more transparent. These results align with the previous studies highlighting the value of digital transformation for better real-time visibility, operational efficiency, and sustainable supply chain (Vasileiou, 2025). Additionally, the regression analysis showed that the overall supply chain performance was explained by the integration of digital technologies with high levels of strength, thus establishing the positive relationship between the integration of digital technologies and the overall supply chain performance (Adamashvili, 2024). The findings are also in line with the previous studies that blockchain technologies enable coordination among stakeholders, lower transactional costs, and build mutual trust among them in supply chain networks (Gondal, 2023). The mediation results also give deeper insights: Traceability and transparency constitute relevant mechanisms that mediate the impact of digital skills on maintainable performance (Halder, 2025).

## Conclusion

The study successfully aimed to investigate how digital technologies, such as blockchain, artificial intelligence, and RFID, can affect food safety and sustainable performance in food supply chains, with traceability and transparency as mediators and regulatory support and tech readiness as moderators. The results verified that digital technologies have a positive impact on the traceability of the supply chain, which in turn has a positive impact on transparency and sustainability performance. The results align with recent research on the role of digital transformation to enhance operational efficiency and supply chain visibility (Vasileiou et al., 2025). Furthermore, the study confirmed the sequential mediation model, underscoring the traceability and transparency of the digital technologies pathway as crucial links between them and their sustainable outcomes (Adamashvili et al., 2024). The results also align with previous research that digital technologies improve coordination, reduce waste in operations, and foster trust between the stakeholders within the supply chain (Gondal et al., 2023). Furthermore, the findings underscore the global shift towards

advanced digital solutions being critical for sustainable and resilient food supply chain systems, as has been increasingly argued and suggested (Halder et al., 2025).

### **Future Research Direction**

For future studies, the proposed study should be continued with the use of longitudinal studies to explore the long-term impact of digital technologies on the performance of the supply chain. Additionally, researchers can examine the use of these technologies in other sectors and in the wider supply chain. In addition, other factors, including organizational culture, innovation capacity, and environmental uncertainty, could be added to future research to gain a better understanding of the process of digital transformation. Future studies could be complemented by the use of advanced statistical techniques and mixed methods approaches. The literature also suggests that there is a need to consider emerging technologies like the Internet of Things (IoT) and big data analytics as other contributors to supply chain performance and sustainability (Taj et al., 2023). Likewise, future research can explore opportunities for using integrated digital ecosystems to improve operational efficiency and traceability (Gbashi & Njobeh, 2024). Furthermore, understanding institutional and contextual factors would facilitate the understanding of the technology adoption and implementation issues in supply chains (Awan, 2021). The successful acceptance of digital technologies in sustainable supply chain systems has also been linked to regulatory and organizational environments (Dehghani et al., 2022; George & Al-Ansari, 2023), with these factors having an influence.

## References

- Abbate, S., Centobelli, P., & Cerchione, R. (2023). The digital and sustainable transition of the agri-food sector. *Technological Forecasting and Social Change*, 187, 122222. <https://doi.org/10.1016/j.techfore.2022.122222>
- Acampora, A., Ruini, L., Mattia, G., Pratesi, C. A., & Lucchetti, M. C. (2023). Towards carbon neutrality in the agri-food sector: Drivers and barriers. *Resources, Conservation and Recycling*, 189, 106755. <https://doi.org/10.1016/j.resconrec.2022.106755>
- Adamashvili, N., Zhizhilashvili, N., & Tricase, C. (2024). The integration of the Internet of things, artificial intelligence, and blockchain technology for advancing the wine supply chain. *Computers*, 13(3), 72. <https://doi.org/10.3390/computers13030072>
- Alamsyah, A., Widiyanesti, S., Wulansari, P., Nurhazidah, E., Dewi, A. S., Rahadian, D., Ramadhani, D. P., Hakim, M. N., & Tyasamesi, P. (2023). Blockchain traceability model in the coffee industry. *Journal of Open Innovation Technology Market and Complexity*, 9(1), 100008. <https://doi.org/10.1016/j.joitmc.2023.100008>
- Awan, S., Ahmed, S., Ullah, F., Nawaz, A., Khan, A., Uddin, M. I., Alharbi, A., Alosaimi, W., & Alyami, H. (2021). IoT with BlockChain: A futuristic approach in agriculture and food supply chain. *Wireless Communications and Mobile Computing*, 2021(1), 1–14. <https://doi.org/10.1155/2021/5580179>
- Azevedo, P., Gomes, J., & Romão, M. (2023). Supply chain traceability using blockchain. *Operations Management Research*, 16(3), 1359–1381. <https://doi.org/10.1007/s12063-023-00359-y>
- Bag, S., Rahman, M. S., Singh, A., Bryde, D., & Graham, G. (2024). Leveraging digital technology capability for circular economy innovation in the food products supply chain: A mixed-method study. *IEEE Transactions on Engineering Management*, 71, 13997–14010. <https://doi.org/10.1109/tem.2024.3435750>
- Ben Hassen, T., & El Bilali, H. (2022). Impacts of the Russia-Ukraine war on global food security: Towards more sustainable and resilient food systems? *Foods (Basel, Switzerland)*, 11(15), 2301. <https://doi.org/10.3390/foods11152301>
- Benmamoun, Z., Khlie, K., Agarwal, V., Jebbor, I., Jha, C. K., & El Kadi, H. (2025). A multicriteria risk management model for Agri-food industrial companies. *Environment Development and Sustainability*. <https://doi.org/10.1007/s10668-025-06584-8>
- Bouzembrak, Y., Liu, N., Mu, W., Gavai, A., Manning, L., Butler, F., & Marvin, H. J. P. (2024). Data driven food fraud vulnerability assessment using Bayesian Network: Spices supply chain. *Food Control*, 164(110616), 110616. <https://doi.org/10.1016/j.foodcont.2024.110616>
- Buyuktepe, O., Catal, C., Kar, G., Bouzembrak, Y., Marvin, H., & Gavai, A. (2025). Food fraud detection using explainable artificial intelligence. *Expert Systems*, 42(1). <https://doi.org/10.1111/exsy.13387>
- Cao, Y., Yi, C., Wan, G., Hu, H., Li, Q., & Wang, S. (2022). An analysis on the role of blockchain-based platforms in agricultural supply chains. *Transportation Research Part E: Logistics and Transportation Review*, 163(102731), 102731. <https://doi.org/10.1016/j.tre.2022.102731>
- Castro Campos, B., & Qi, X. (2024). A literature review on the drivers and barriers of organic food consumption in China. *Agricultural and Food Economics*, 12(1). <https://doi.org/10.1186/s40100-024-00312-y>
- Dasaklis, T. K., Voutsinas, T. G., Tsoulfas, G. T., & Casino, F. (2022). A systematic literature review of blockchain-enabled supply chain traceability implementations. *Sustainability*, 14(4), 2439. <https://doi.org/10.3390/su14042439>
- Dehghani, M., Popova, A., & Gheitanchi, S. (2022). Factors impacting digital transformations of the food industry by adoption of blockchain technology. *Journal of Business & Industrial Marketing*, 37(9), 1818–1834. <https://doi.org/10.1108/jbim-12-2020-0540>
- Dora, M., Kumar, A., Mangla, S. K., Pant, A., & Kamal, M. M. (2022). Critical success factors influencing artificial intelligence adoption in food supply chains. *International Journal of Production Research*, 60(14), 4621–4640. <https://doi.org/10.1080/00207543.2021.1959665>

- Essien, A., Chukwukelu, G. O., Kazantsev, N., & Subramanian, N. (2024). Unveiling the factors influencing transparency and traceability in agri-food supply chains: an interconnected framework. *Supply Chain Management: An International Journal*, 29(3), 602–619. <https://doi.org/10.1108/scm-02-2023-0083>
- Gbashi, S., & Njobeh, P. B. (2024). Enhancing food integrity through artificial intelligence and machine learning: A comprehensive review. *Applied Sciences (Basel, Switzerland)*, 14(8), 3421. <https://doi.org/10.3390/app14083421>
- George, W., & Al-Ansari, T. (2023). Review of blockchain applications in food supply chains. *Blockchains*, 1(1), 34–57. <https://doi.org/10.3390/blockchains1010004>
- Gondal, M. U. A., Khan, M. A., Haseeb, A., Albarakati, H. M., & Shabaz, M. (2023). A secure food supply chain solution: blockchain and IoT-enabled container to enhance the efficiency of shipment for strawberry supply chain. *Frontiers in Sustainable Food Systems*, 7(1294829). <https://doi.org/10.3389/fsufs.2023.1294829>
- Halder, S., Rafiqul Islam, M., Mamun, Q., Mahboubi, A., Walsh, P., & Zahidul Islam, M. (2025). A comprehensive survey on AI-enabled secure social industrial Internet of Things in the agri-food supply chain. *Smart Agricultural Technology*, 11(100902), 100902. <https://doi.org/10.1016/j.atech.2025.100902>
- Hassan, S., Zaman, S., & Alam, S. (2023). A systematic review in the world of the metaverse. *Market Forces*, 18(1), 135–150. <https://doi.org/10.51153/mf.v18i1.622>
- Hassoun, A., Alhaj Abdullah, N., Ait-Kaddour, A., Ghellam, M., Beşir, A., Zannou, O., Önal, B., Aadil, R. M., Lorenzo, J. M., Mousavi Khaneghah, A., & Regenstein, J. M. (2024). Food traceability 4.0 as part of the fourth industrial revolution: key enabling technologies. *Critical Reviews in Food Science and Nutrition*, 64(3), 873–889. <https://doi.org/10.1080/10408398.2022.2110033>
- Kamal, M. H., Zaman, S. U., Alam, S. H., Iqbal, M., & Dashnyam, A. (2024). Sustaining Pakistan's Economy through Strategic Gas Planning and Predictive Analytics. *ILMA JOURNAL OF SOCIAL SCIENCES & ECONOMICS*, 5(2).
- Khan, E. S., Zaman, S. U., & Alam, S. H. (2025). How Socio-economic issues impact in the real estate industry A case study of contemporary Karachi. *JOURNAL OF LAW, SOCIAL AND MANAGEMENT SCIENCES*, 4(1), 1–10. <https://jlsms.org/index.php/jlsms/article/view/95>
- Khoso, S., Zaman, D. S. U., & Alam, S. H. (2025). Cultural effect of health and information disclosure on brand loyalty in emerging market. *Journal of Social Signs Review*, 3(4), 74–100. <https://doi.org/10.63075/jssr.v3i4.203>
- Morchid, A., Ismail, A., Khalid, H. M., Qjidaa, H., & Alami, R. E. (2025). Blockchain and IoT technologies in smart farming to enhance the efficiency of the agri-food supply chain: A review of applications, benefits, and challenges. *Internet of Things (Amsterdam, Netherlands)*, 33(101733), 101733. <https://doi.org/10.1016/j.iot.2025.101733>
- Plakantara, S. P., & Karakitsiou, A. (2025). Transforming agrifood supply chains with digital technologies: A systematic review of safety and quality risk management. *Operations Research Forum*, 6(3). <https://doi.org/10.1007/s43069-025-00511-3>
- Qian, J., Ruiz-Garcia, L., Fan, B., Robla Villalba, J. I., McCarthy, U., Zhang, B., Yu, Q., & Wu, W. (2020). Food traceability system from governmental, corporate, and consumer perspectives in the European Union and China: A comparative review. *Trends in Food Science & Technology*, 99, 402–412. <https://doi.org/10.1016/j.tifs.2020.03.025>
- Rossi, S., Gemma, S., Borghini, F., Perini, M., Butini, S., Carullo, G., & Campiani, G. (2025). Agri-food traceability today: Advancing innovation towards efficiency, sustainability, ethical sourcing, and safety in food supply chains. *Trends in Food Science & Technology*, 163(105154), Not Available. <https://doi.org/10.1016/j.tifs.2025.105154>
- Sarkar, B. D., Sharma, I., & Shardeo, V. (2025). A multi-method examination of barriers to traceability in Industry 5.0-enabled digital food supply chains. *International Journal of Logistics Management*, 36(2), 354–380. <https://doi.org/10.1108/ijlm-01-2024-0010>

- Sri Vigna Hema, V., & Manickavasagan, A. (2024). Blockchain implementation for food safety in supply chain: A review. *Comprehensive Reviews in Food Science and Food Safety*, 23(5), e70002. <https://doi.org/10.1111/1541-4337.70002>
- Taj, S., Imran, A. S., Kastrati, Z., Daudpota, S. M., Memon, R. A., & Ahmed, J. (2023). IoT-based supply chain management: A systematic literature review. *Internet of Things (Amsterdam, Netherlands)*, 24(100982), 100982. <https://doi.org/10.1016/j.iot.2023.100982>
- Tsolakis, N., Schumacher, R., Dora, M., & Kumar, M. (2022). Artificial intelligence and blockchain implementation in supply chains: a pathway to sustainability and data monetisation? *Annals of Operations Research*, 327(1), 1–54. <https://doi.org/10.1007/s10479-022-04785-2>
- Uz Zaman, S., Shahryar Ali, S., Hasnain Alam, S., & Hassan Kamal, M. (2025). Assessing student's behavioral intentions towards AI based learning tools. *Journal of Asian Development Studies*, 14(1), 656–672. <https://doi.org/10.62345/jads.2025.14.1.50>
- Vasileiou, M., Kyrgiakos, L. S., Kleisiari, C., Lappas, P. Z., Tsinopoulos, C., Kleftodimos, G., Ntemou, A., Kateris, D., Moulogianni, C., & Vlontzos, G. (2025). Digital transformation of food supply chain management using blockchain: A systematic literature review towards food safety and traceability. *Business & Information Systems Engineering*. <https://doi.org/10.1007/s12599-025-00948-0>
- Vazquez Melendez, E. I., Bergey, P., & Smith, B. (2024). Blockchain technology for supply chain provenance: increasing supply chain efficiency and consumer trust. *Supply Chain Management: An International Journal*, 29(4), 706–730. <https://doi.org/10.1108/scm-08-2023-0383>
- Verna, E., Genta, G., & Galetto, M. (2025). Enhanced food quality by digital traceability in food processing industry. *Food Engineering Reviews*, 17(2), 359–383. <https://doi.org/10.1007/s12393-024-09392-4>
- Wahyuni, H. C., Rosid, M. A., Azara, R., & Voak, A. (2024). Blockchain technology design based on food safety and halal risk analysis in the beef supply chain with FMEA-FTA. *Journal of Engineering Research*. <https://doi.org/10.1016/j.jer.2024.02.002>
- Xue, Y., Yan, J., Mohsin, M., & Mehak, A. (2025). Supply chain risks in agri-food systems: a comprehensive review of economic vulnerabilities and mitigation approaches. *Frontiers in Sustainable Food Systems*, 9(1649834). <https://doi.org/10.3389/fsufs.2025.1649834>
- Yadav, V. S., & Raut, R. (2024). Climate neutrality in agriculture food supply chain: an integrated WINGS-GRID framework. *International Journal of Logistics Management*, 35(3), 892–915. <https://doi.org/10.1108/ijlm-03-2023-0110>
- Zhang, A., Maxwell, C., Tacconi, F., Lythall, A., Smith, D., & Guan, X. (2025). Supporting ecosystem for farmers' food traceability participation: A systematic review. *Journal of Agriculture and Food Research*, 23(102288), 102288. <https://doi.org/10.1016/j.jafr.2025.102288>