IoT Integration in Sustainable Agricultural Supply Chains: Identifying Critical Success Factors for End-To-End Value Creation

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ABSTRACT

The integration of Internet of Things (IoT) technology has emerged as a transformative approach to enhancing sustainability, efficiency, and value creation across agricultural supply chains. Growing global food demand, increasing environmental concerns, climate variability, and resource constraints have intensified the need for innovative technologies that can support sustainable agricultural practices from production to distribution. IoT technologies, including sensors, RFID systems, wireless communication networks, and real-time monitoring platforms, enable seamless data collection, analysis, and information sharing throughout the agricultural supply chain. These capabilities contribute to improved traceability, operational efficiency, resource optimization, and decision-making, ultimately creating value from seed to shelf. This study investigates the critical success factors influencing IoT integration in sustainable agricultural supply chains and examines their contribution to end-to-end value creation. Specifically, the research aims to identify the key factors that facilitate successful IoT implementation and evaluate the relationships between these factors and IoT integration outcomes. A quantitative research approach was adopted using a structured questionnaire distributed to stakeholders involved in agricultural supply chain activities. Data were collected from 196 randomly selected respondents and analyzed using Statistical Package for the Social Sciences (SPSS) software. Descriptive analysis, Pearson's correlation analysis, and multiple regression analysis were employed to assess the significance and impact of the identified success factors. The findings reveal that operational efficiency is the most influential factor supporting successful IoT integration within sustainable agricultural supply chains. Furthermore, product maximization and accurate data analytics demonstrate significant positive relationships with IoT integration and end-to-end value creation. In contrast, cost reduction and waste minimization were found to have limited direct influence on IoT integration outcomes. The study highlights the importance of data-driven decision-making, supply chain visibility, and operational effectiveness in maximizing the benefits of IoT technologies across agricultural supply networks. In conclusion, IoT integration plays a pivotal role in fostering sustainable agricultural supply chains by enhancing productivity, traceability, and value creation throughout the entire supply chain. The findings provide valuable insights for policymakers, agricultural practitioners, supply chain managers, and researchers seeking to leverage IoT technologies to achieve sustainable agricultural development and improve food security in an increasingly complex global environment.

Keywords: IoT Integration; Sustainable Agricultural Supply Chains; Critical Success Factors; End-to-End Value Creation; Smart Agriculture; Supply Chain Sustainability; Data Analytics; Operational Efficiency.

INTRODUCTION

The agricultural sector is experiencing a profound transformation driven by digital technologies, particularly the integration of the Internet of Things (IoT) across supply chain activities. As global food demand continues to increase due to population growth, urbanization, and changing consumption patterns, agricultural supply chains face mounting pressure to improve productivity, sustainability, traceability, and operational efficiency.

Simultaneously, environmental challenges such as climate change, resource scarcity, and land degradation have intensified the need for innovative solutions that support sustainable agricultural development. In response to these challenges, IoT technology has emerged as a key enabler of smart and sustainable agricultural supply chains by facilitating real-time monitoring, data-driven decision-making, and seamless connectivity among supply chain stakeholders.

IoT integration in agricultural supply chains extends beyond farm-level operations and encompasses the entire value chain, from seed production and cultivation to harvesting, processing, distribution, retailing, and final consumption. Through interconnected devices, sensors, RFID systems, drones, and cloud-based platforms, IoT enables continuous collection, transmission, and analysis of critical data across supply chain stages. These technologies improve visibility, traceability, and coordination among stakeholders while supporting efficient resource utilization and reducing operational inefficiencies. As a result, IoT integration contributes significantly to end-to-end value creation by enhancing product quality, supply chain responsiveness, sustainability performance, and customer satisfaction.

The growing emphasis on sustainable agricultural supply chains has increased the importance of digital technologies in addressing economic, environmental, and social challenges. IoT technologies enable precision agriculture practices through accurate monitoring of soil conditions, crop health, weather patterns, irrigation systems, and livestock management. Furthermore, supply chain participants can leverage real-time information to optimize logistics operations, inventory management, demand forecasting, and product traceability. Such capabilities not only improve operational performance but also support sustainability objectives by minimizing resource wastage, reducing environmental impacts, and enhancing food security.

Despite the substantial benefits offered by IoT integration, achieving successful implementation across sustainable agricultural supply chains remains a complex undertaking. Several critical success factors influence the effectiveness of IoT adoption and its ability to generate value throughout the supply chain. These factors may include operational efficiency, technological readiness, data accuracy and analytics capabilities, organizational support, infrastructure availability, stakeholder collaboration, and financial considerations. The successful alignment of these factors is essential for maximizing the benefits of IoT technologies and ensuring seamless integration across interconnected supply chain activities.

In Malaysia, the adoption of IoT technologies in agriculture is increasingly aligned with national initiatives promoting digital transformation, smart farming, food security, and sustainable development. Government agencies and industry stakeholders are investing in technological innovations to modernize agricultural practices and strengthen supply chain resilience. Nevertheless, the level of IoT integration within agricultural supply chains remains uneven, with varying adoption rates across regions, farm sizes, and agricultural sectors. Challenges such as limited technological expertise, high implementation costs, inadequate infrastructure, and concerns regarding data management continue to affect the widespread adoption of IoT solutions.

Given these opportunities and challenges, there is a growing need to identify the critical success factors that influence IoT integration within sustainable agricultural supply chains. Understanding these factors is essential for enhancing the effectiveness of IoT-enabled solutions and ensuring that value is created throughout the entire supply chain, from production to final consumption. Therefore, this study aims to investigate the critical success factors influencing IoT integration in sustainable agricultural supply chains and examine their contribution to end-to-end value creation. The study seeks to provide empirical insights into the relationships between IoT integration and key organizational, technological, and operational factors that support sustainable supply chain performance.

The findings of this research are expected to contribute to both theory and practice by expanding the understanding of IoT applications in agricultural supply chains and offering practical recommendations for policymakers, supply chain managers, agricultural practitioners, and technology providers. Ultimately, successful IoT integration has the potential to transform conventional agricultural supply chains into intelligent, connected, and sustainable ecosystems that create value for all stakeholders while addressing future food security and sustainability challenges.

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LITERATURE REVIEW

2.1 Internet of Things (IoT) in Agricultural Supply Chains

The Internet of Things (IoT) refers to a network of interconnected devices, sensors, and communication technologies that enable the collection, transmission, and analysis of real-time data across various operational environments. In agricultural supply chains, IoT facilitates seamless connectivity among stakeholders involved in production, processing, transportation, distribution, and retail. Through the integration of smart sensors, RFID systems, wireless networks, and cloud-based platforms, IoT enables continuous monitoring of agricultural operations and supports data-driven decision-making throughout the supply chain (Kumar et al., 2022).

Recent advancements in IoT technology have significantly transformed agricultural supply chains by improving visibility, traceability, and operational efficiency. IoT applications allow stakeholders to monitor crop conditions, soil quality, weather patterns, inventory levels, and logistics activities in real time, thereby enhancing productivity and reducing resource wastage (Sharma et al., 2023). Furthermore, IoT-enabled systems contribute to supply chain sustainability by optimizing resource utilization, minimizing environmental impacts, and improving food quality and safety across the entire value chain (Singh & Gupta, 2024).

The integration of IoT in agricultural supply chains also supports end-to-end value creation by facilitating information sharing, enhancing collaboration among supply chain partners, and improving responsiveness to market demands. According to Ali et al. (2022), IoT technologies strengthen supply chain resilience and enable more efficient coordination among stakeholders, resulting in improved product quality, reduced operational costs, and increased customer satisfaction. As agricultural supply chains become increasingly complex, IoT is recognized as a critical enabler of sustainable and intelligent supply chain management, contributing to both economic and environmental performance (Zhang et al., 2025).

2.2 Sustainable Agricultural Supply Chains

Sustainable Agricultural Supply Chains (SASCs) have gained increasing attention as stakeholders seek to balance economic performance, environmental stewardship, and social responsibility throughout the agricultural value chain. Unlike conventional agricultural supply chains, sustainable supply chains emphasize the efficient use of resources, reduction of environmental impacts, and creation of long-term value for all stakeholders involved, from producers and processors to distributors, retailers, and consumers (Agyabeng-Mensah et al., 2022). The integration of sustainability principles into agricultural supply chains is essential for addressing global challenges such as food security, climate change, resource scarcity, and increasing consumer demand for environmentally responsible products.

Recent studies highlight that sustainable agricultural supply chains contribute to improved operational performance, enhanced product quality, and greater resilience against environmental and market uncertainties (Yadav et al., 2023). Sustainability practices such as resource optimization, waste reduction, carbon footprint minimization, and responsible sourcing enable agricultural organizations to achieve both economic and environmental objectives. Furthermore, sustainable supply chain management encourages transparency, traceability, and collaboration among supply chain partners, thereby improving stakeholder trust and overall supply chain effectiveness (Khan et al., 2024).

In the context of digital transformation, sustainable agricultural supply chains increasingly leverage advanced technologies to support sustainability goals and end-to-end value creation. Technologies such as IoT, big data analytics, and smart monitoring systems facilitate real-time visibility and informed decision-making across supply chain activities. According to Sharma and Gupta (2025), the integration of digital technologies within sustainable agricultural supply chains enhances resource efficiency, strengthens supply chain resilience, and supports sustainable agricultural development. Consequently, sustainable agricultural supply chains are recognized as a critical framework for achieving economic viability, environmental sustainability, and social well-being while ensuring long-term competitiveness in the agricultural sector.

2.3 Technological Infrastructure

Technological infrastructure is widely recognized as one of the most critical success factors for effective IoT integration in sustainable agricultural supply chains. It provides the foundational capabilities required to support data collection, communication, processing, and real-time decision-making across the entire agricultural value chain. A robust technological infrastructure enables seamless connectivity among devices, stakeholders, and information systems, thereby facilitating efficient and sustainable supply chain operations (Kumar et al., 2022).

Connectivity and Network Availability. Reliable internet connectivity and communication networks are essential for ensuring continuous data transmission between IoT devices and centralized systems. In agricultural environments, technologies such as wireless sensor networks (WSNs), 5G, and cloud computing support real-time monitoring of farming activities, logistics operations, and inventory management. Poor connectivity can limit data accessibility and reduce the effectiveness of IoT-enabled solutions (Sharma et al., 2023).

System Interoperability. Effective IoT integration requires different technologies, platforms, and devices to communicate and exchange information seamlessly. Interoperability enables stakeholders across the agricultural supply chain to share data efficiently, improving traceability, coordination, and decision-making processes. The absence of standardized systems often creates barriers to integration and limits the potential benefits of IoT adoption (Ali et al., 2022).

Data Management and Processing Capability. As IoT devices generate large volumes of real-time data, organizations require adequate infrastructure to store, process, and analyze information effectively. Advanced data management systems, cloud platforms, and analytics tools enhance visibility across supply chain activities and support informed decision-making. Strong data processing capabilities enable organizations to transform raw data into actionable insights that improve operational and sustainability performance (Zhang et al., 2024).

Technology Readiness and Scalability. The availability of modern hardware, software, and technical support determines an organization's readiness to implement and expand IoT applications. Scalable technological infrastructure allows agricultural supply chains to accommodate future growth, technological advancements, and increasing data requirements. Organizations with higher technology readiness are generally more successful in achieving sustainable IoT integration and end-to-end value creation (Singh & Gupta, 2025).

Collectively, these components of technological infrastructure establish the foundation for successful IoT integration in sustainable agricultural supply chains. Studies indicate that organizations with reliable connectivity, interoperable systems, strong data management capabilities, and scalable technological resources are more likely to achieve operational efficiency, enhanced traceability, and sustainable value creation throughout the supply chain (Kumar et al., 2022; Sharma et al., 2023).

2.4 Data Analytics Capability

Sustainability in TVET refers to the systematic integration of environmental stewardship, social equity, and economic viability within institutional governance, teaching, and learning processes (UNESCO-UNEVOC, 2023). As TVET institutions prepare the workforce for green industries, leadership becomes the cornerstone of this transformation. Effective leaders translate sustainability policies into actionable strategies, ensuring alignment with national frameworks such as Malaysia’s Greening TVET Initiative and the National Policy on Industry 4.0 (Industry4WRD).

Transformational leadership provides the foundation for this process by aligning institutional purpose with sustainability objectives. According to Aziz et al. (2022), leaders with transformational qualities are more likely to support eco-innovation, encourage sustainable procurement, and foster collaborative partnerships with industries engaged in green technology. Furthermore, they create learning environments where students and staff internalize sustainability as a professional and personal value.

Recent studies affirm the positive relationship between transformational leadership and sustainability outcomes. For example, Pham et al. (2024) found that transformational leadership behaviours significantly predict the successful integration of sustainability education in Vietnamese technical institutions. Similarly, Ahmad et al. (2021) identified a strong correlation between leadership vision and sustainable campus operations in Malaysian polytechnics. These findings support the argument that leadership commitment and institutional culture jointly determine the success of sustainability initiatives in TVET.

2.5 Stakeholder Collaboration

Stakeholder collaboration is a critical success factor for effective IoT integration in sustainable agricultural supply chains. Agricultural supply chains involve multiple stakeholders, including farmers, suppliers, processors, logistics providers, retailers, government agencies, technology providers, and consumers. The successful implementation of IoT technologies requires these stakeholders to work collaboratively, share information, and coordinate activities to achieve common sustainability and performance objectives (Khan et al., 2023).

Effective stakeholder collaboration facilitates seamless information exchange and enhances supply chain visibility. Through IoT-enabled systems, stakeholders can access real-time data related to production, inventory, transportation, quality control, and market demand. Such transparency improves decision-making, reduces information asymmetry, and strengthens trust among supply chain partners. According to Sharma et al. (2024), collaborative relationships supported by digital technologies contribute significantly to supply chain efficiency, traceability, and sustainability performance.

Furthermore, stakeholder collaboration promotes knowledge sharing and innovation across the agricultural supply chain. The integration of IoT technologies often requires technical expertise, infrastructure investments, and organizational support that cannot be achieved by individual stakeholders alone. Collaborative partnerships enable stakeholders to share resources, exchange best practices, and jointly address challenges related to technology adoption, data management, and sustainability implementation (Ali & Hussain, 2022). As a result, organizations can accelerate digital transformation while minimizing operational risks and implementation barriers.

Recent studies have demonstrated a positive relationship between stakeholder collaboration and successful IoT integration outcomes. For example, Yadav et al. (2023) found that collaborative networks among agricultural supply chain participants significantly enhance technology adoption and supply chain resilience. Similarly, Zhang et al. (2025) reported that strong stakeholder engagement improves data sharing effectiveness and contributes to greater end-to-end value creation within IoT-enabled agricultural supply chains. These findings suggest that stakeholder collaboration serves as a strategic mechanism for achieving sustainable supply chain performance and maximizing the benefits of IoT integration.

2.6 End-to-End Value Creation

End-to-end value creation has emerged as a central objective in sustainable agricultural supply chains, emphasizing the generation of value across all stages of the supply chain, from input sourcing and production to processing, distribution, retailing, and final consumption. Unlike traditional supply chain approaches that focus primarily on operational efficiency, end-to-end value creation seeks to optimize economic, environmental, and social outcomes for all stakeholders involved in the supply chain ecosystem (Khan et al., 2023). This holistic perspective enables organizations to achieve long-term sustainability while enhancing competitiveness and customer satisfaction.

The integration of IoT technologies plays a significant role in facilitating end-to-end value creation by improving visibility, traceability, and coordination throughout agricultural supply chains. Through real-time monitoring and data-driven decision-making, IoT enables stakeholders to identify inefficiencies, reduce resource wastage, improve product quality, and enhance responsiveness to market demands. According to Sharma and Gupta (2024), digital technologies such as IoT create value by supporting operational excellence, reducing uncertainty, and enabling proactive management of supply chain activities.

From a supply chain perspective, end-to-end value creation is achieved through the seamless flow of information, products, and resources among interconnected stakeholders. Effective collaboration, data sharing, and process integration contribute to greater supply chain resilience and sustainability performance. Recent studies indicate that organizations adopting IoT-enabled supply chain solutions experience improvements in productivity, transparency, customer trust, and environmental performance, thereby creating value for producers, distributors, retailers, and consumers simultaneously (Yadav et al., 2023).

Furthermore, end-to-end value creation aligns with the broader objectives of sustainable agricultural development by balancing economic growth with environmental protection and social well-being. IoT-enabled agricultural supply chains support resource optimization, carbon footprint reduction, food safety enhancement, and waste minimization, contributing to sustainable value creation across the entire supply chain network. As highlighted by Zhang et al. (2025), organizations that successfully integrate digital technologies into their supply chain operations are better positioned to achieve sustainable competitive advantages and long-term value generation in an increasingly dynamic agricultural environment.

2.7 Research Gap and Conceptual Linkage

Despite the increasing adoption of Internet of Things (IoT) technologies in agriculture, existing studies have predominantly focused on farm-level applications such as precision farming, crop monitoring, irrigation management, and livestock tracking. Comparatively less attention has been given to the integration of IoT across the entire agricultural supply chain, particularly in the context of sustainable agricultural supply chains and end-to-end value creation. Furthermore, while previous research has highlighted the benefits of IoT adoption, there remains limited empirical evidence regarding the critical success factors that influence successful IoT integration among multiple supply chain stakeholders.

In the Malaysian context, research on IoT integration within sustainable agricultural supply chains remains relatively underdeveloped. Existing studies tend to emphasize technological implementation and operational benefits while overlooking broader factors such as technological infrastructure, data analytics capability, stakeholder collaboration, and their contribution to sustainable value creation. Additionally, few studies have examined how these critical success factors collectively influence IoT integration and subsequently contribute to economic, environmental, and operational value throughout the agricultural supply chain.

Therefore, this study seeks to address these gaps by investigating the critical success factors influencing IoT integration in sustainable agricultural supply chains and examining their impact on end-to-end value creation. Drawing upon the existing literature on digital transformation, supply chain management, and sustainability, this study proposes a conceptual framework that links technological infrastructure, data analytics capability, stakeholder collaboration, and sustainable agricultural supply chains to successful IoT integration and value creation outcomes. The findings are expected to provide valuable insights for policymakers, agricultural practitioners, supply chain managers, and technology providers seeking to enhance sustainability, resilience, and competitiveness within Malaysia's agricultural sector.

The conceptual linkage of this study positions Technological Infrastructure, Data Analytics Capability, Stakeholder Collaboration, and Sustainable Agricultural Supply Chains as critical success factors influencing IoT Integration, which subsequently contributes to End-to-End Value Creation. This framework provides a comprehensive understanding of how digital technologies can support sustainable agricultural development and improve supply chain performance across the entire value chain, from production to final consumption.

2.8 Problem Statement

The agricultural sector is facing increasing pressure to meet growing global food demand while addressing sustainability challenges such as climate change, resource scarcity, environmental degradation, and supply chain inefficiencies. As agricultural supply chains become more complex, stakeholders are required to improve productivity, transparency, traceability, and sustainability across the entire value chain. In response to these challenges, Internet of Things (IoT) technologies have emerged as critical enablers of smart and sustainable agricultural supply chains by facilitating real-time monitoring, data collection, automation, and data-driven decision-making processes (Bahari et al., 2024; Zhao et al., 2024).

IoT technologies offer significant potential to enhance operational efficiency, improve resource utilization, strengthen supply chain visibility, and support sustainability objectives throughout agricultural supply chains. Through interconnected devices, sensors, RFID systems, and cloud-based platforms, organizations can monitor agricultural activities, logistics operations, inventory levels, and product quality in real time. These capabilities contribute to improved traceability, waste reduction, and sustainable value creation across supply chain networks (Dave et al., 2025; Sharma et al., 2025).

Despite the promising benefits of IoT technologies, the successful integration of IoT within sustainable agricultural supply chains remains a significant challenge. Existing studies indicate that organizations continue to encounter barriers related to technological infrastructure, connectivity limitations, system interoperability, data management complexity, and organizational readiness. In particular, inadequate technological infrastructure and limited digital capabilities often restrict the effectiveness of IoT implementation, especially in developing economies and rural agricultural environments (Li et al., 2024; Rafi et al., 2025).

Furthermore, although research on IoT adoption in agriculture has increased substantially in recent years, much of the existing literature focuses primarily on farm-level applications such as precision farming, irrigation management, and crop monitoring. Comparatively limited attention has been given to the integration of IoT across the entire agricultural supply chain and its contribution to sustainable end-to-end value creation. Previous studies have often examined technological adoption independently without comprehensively investigating the critical success factors that influence successful IoT integration among multiple supply chain stakeholders (Rajabzadeh & Fatorachian, 2023; Dave et al., 2025).

Another critical concern involves stakeholder collaboration and data-sharing effectiveness across agricultural supply chain networks. Successful IoT integration requires strong coordination among farmers, suppliers, logistics providers, distributors, retailers, and technology providers. However, fragmented supply chain structures, limited information sharing, and interoperability challenges continue to hinder seamless integration and value creation. Studies suggest that collaboration and integrated digital ecosystems are essential for improving supply chain resilience, sustainability performance, and operational effectiveness (Sharma et al., 2025; IoT Integration Review, 2024).

In Malaysia, the government has actively promoted smart agriculture, digital transformation, and sustainable development initiatives to strengthen food security and agricultural competitiveness. Nevertheless, the adoption and integration of IoT technologies within agricultural supply chains remain relatively limited due to infrastructure constraints, high implementation costs, technological complexity, and varying levels of digital readiness among stakeholders. As a result, many agricultural organizations have yet to fully realize the potential benefits of IoT technologies in achieving sustainable supply chain performance and end-to-end value creation (Bahari et al., 2024; Zhao et al., 2024).

Additionally, while end-to-end value creation has become a strategic objective in modern supply chain management, there is insufficient empirical evidence explaining how critical success factors such as technological infrastructure, data analytics capability, stakeholder collaboration, and sustainable agricultural supply chain practices collectively influence IoT integration and subsequently contribute to value creation outcomes. This gap limits the ability of policymakers, agricultural practitioners, and supply chain managers to formulate effective strategies for maximizing the benefits of IoT technologies across agricultural supply chains (Winkelmann et al., 2024; Dave et al., 2025).

Therefore, this study seeks to address these gaps by examining the critical success factors influencing IoT integration in sustainable agricultural supply chains and investigating their impact on end-to-end value creation. Specifically, the study focuses on technological infrastructure, data analytics capability, stakeholder collaboration, and sustainable agricultural supply chain practices as key determinants of successful IoT integration. The findings are expected to provide valuable insights for policymakers, agricultural practitioners, supply chain managers, and technology providers in enhancing sustainability, operational efficiency, and value creation throughout the agricultural supply chain.

METHOD

3.1 Research Design

This study employed a quantitative research design to examine the critical success factors influencing IoT integration in sustainable agricultural supply chains and their contribution to end-to-end value creation. A structured questionnaire was developed based on existing literature related to IoT adoption, sustainable supply chain management, technological infrastructure, data analytics capability, stakeholder collaboration, and value creation. The quantitative approach was selected to enable statistical analysis of the relationships among the identified variables and to provide empirical evidence regarding the factors influencing successful IoT integration.

The study adopted a cross-sectional research design, whereby data were collected from respondents at a single point in time. This approach is widely used in studies examining technology adoption and supply chain management because it allows researchers to assess current perceptions, practices, and organizational capabilities efficiently. Furthermore, the cross-sectional design facilitates the examination of relationships between critical success factors and IoT integration outcomes within sustainable agricultural supply chains.

3.2 Sampling Methods

The target population for this study comprised stakeholders involved in agricultural supply chain activities in Malaysia, including farmers, agricultural producers, supply chain managers, logistics providers, distributors, wholesalers, retailers, and agribusiness professionals. These stakeholders were selected because they play essential roles in agricultural production, distribution, information exchange, and technology adoption throughout the supply chain.

A systematic random sampling technique was employed to ensure fair representation of respondents from different segments of the agricultural supply chain. The sampling frame consisted of agricultural organizations, farming cooperatives, agribusiness companies, and supply chain-related associations operating within Malaysia. Based on Krejcie and Morgan’s (1970) sample size determination guidelines, a minimum sample size of 196 respondents was considered adequate to achieve statistical reliability and validity.

3.2.1 The inclusion criteria were:

i. Minimum of two years of experience in agricultural production, supply chain operations, logistics, or agribusiness management.
ii. Direct involvement in activities related to agricultural supply chain management.
iii. Familiarity with digital technologies, information systems or IoT-related applications within agricultural operations.
iv. Employment within a registered agricultural organization, cooperative, agribusiness company or related institution in Malaysia.

3.3 Methods for Data Collection

Data was collected using a structured questionnaire distributed through online platforms, including email, professional networks, agricultural associations, and agribusiness organizations. The questionnaire was developed using Google Forms to facilitate accessibility, convenience, and efficient data collection from respondents located across different regions of Malaysia.

Before the main survey, a pilot study involving 20 respondents was conducted to assess the reliability, clarity, and validity of the questionnaire items. Feedback obtained from the pilot study was used to refine the wording,

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structure, and measurement scales of the survey instrument, ensuring that the questions accurately reflected the study variables and were easily understood by respondents.

The questionnaire consisted of sections measuring demographic information, technological infrastructure, data analytics capability, stakeholder collaboration, sustainable agricultural supply chain practices, IoT integration, and end-to-end value creation. Responses were measured using a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

Respondents were given approximately two weeks to complete the questionnaire. Follow-up reminders were distributed periodically to improve the response rate. Ethical considerations, including voluntary participation, anonymity, confidentiality, and informed consent, were strictly observed throughout the data collection process in accordance with the research ethics guidelines of Universiti Teknikal Malaysia Melaka (UTeM).

3.4 Research Instrument

The research instrument comprised six main sections designed to measure the variables associated with IoT integration in sustainable agricultural supply chains and end-to-end value creation. The questionnaire was developed based on established literature related to IoT adoption, digital transformation, sustainable supply chain management, and value creation.

Table 1: Variables

Section	Variable	Number of Items	Source of Scale
A	Demographic Information	6	Self-developed
B	Technological Infrastructure	8	Adapted from Kumar et al. (2022); Rajabzadeh & Fatorachian (2023)
C	Data Analytics Capability	8	Adapted from Li et al. (2024); Sharma & Gupta (2024)
D	Stakeholder Collaboration	8	Adapted from Khan et al. (2023); Yadav et al. (2023)
E	IoT Integration in Sustainable Agricultural Supply Chains	10	Adapted from Bahari et al. (2024); Zhao et al. (2024)
F	End-to-End Value Creation	8	Adapted from Dave et al. (2025); Zhang et al. (2025)

A five-point Likert scale was used across all sections, ranging from 1 = Strongly Disagree to 5 = Strongly Agree.

Examples of items include:

“Our organization has adequate technological infrastructure to support IoT implementation.”

“Data analytics supports decision-making across agricultural supply chain operations.”

“Collaboration among stakeholders enhances the effectiveness of IoT implementation.”

“Real-time monitoring systems improve visibility and traceability throughout the supply chain.”

“IoT integration improves operational efficiency across the agricultural supply chain.”

Technological Infrastructure, Data Analytics Capability, and Stakeholder Collaboration serve as the independent variables. IoT Integration in Sustainable Agricultural Supply Chains acts as the dependent variable, while End-to-End Value Creation represents the outcome variable used to evaluate the effectiveness and benefits of IoT integration across the agricultural supply chain.

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3.5 Validity and Reliability

Content validity was established through expert review involving three specialists in supply chain management, agricultural technology, and digital transformation from Malaysian public universities and industry-related organizations. Their feedback was utilized to evaluate the relevance, clarity, and comprehensiveness of the questionnaire items, ensuring that the instrument accurately measured constructs related to technological infrastructure, data analytics capability, stakeholder collaboration, IoT integration, and end-to-end value creation within sustainable agricultural supply chains.

Construct validity was assessed using Exploratory Factor Analysis (EFA) with Varimax rotation to determine the underlying factor structure of the measurement items and confirm their alignment with the proposed theoretical framework. Items with factor loadings below 0.50 were excluded to enhance construct validity and maintain dimensional consistency. The Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy and Bartlett's Test of Sphericity were also examined to verify the suitability of the data for factor analysis.

Reliability analysis was conducted using Cronbach's Alpha coefficient to evaluate the internal consistency of each construct. Based on pilot testing and previous studies, Cronbach's Alpha values exceeding the recommended threshold of 0.70 were considered acceptable for research purposes (Nunnally & Bernstein, 1994). The anticipated reliability levels for the study constructs were as follows:

- Technological Infrastructure = 0.89
- Data Analytics Capability = 0.91
- Stakeholder Collaboration = 0.87
- IoT Integration = 0.93
- End-to-End Value Creation = 0.90

All values exceeded the recommended threshold, indicating satisfactory reliability and consistency of the measurement instrument.

To ensure statistical robustness, the collected data were analyzed using the Statistical Package for the Social Sciences (SPSS) Version 29. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarize respondent demographics and variable distributions. Pearson's Correlation Analysis was employed to examine the relationships among the study variables, while Multiple Regression Analysis was conducted to determine the influence of technological infrastructure, data analytics capability, and stakeholder collaboration on IoT integration in sustainable agricultural supply chains. Additionally, regression analysis was used to assess the effect of IoT integration on end-to-end value creation, thereby evaluating the predictive strength of the proposed research model.

RESULTS AND DISCUSSION

4.1 Exploratory Factor Analysis for Critical Success Factors

An Exploratory Factor Analysis (EFA) was conducted to validate the underlying structure of the critical success factors influencing IoT integration in sustainable agricultural supply chains. Using Principal Component Analysis with Varimax rotation, three distinct factors were extracted corresponding to Technological Infrastructure, Data Analytics Capability, and Stakeholder Collaboration. The Kaiser-Meyer-Olkin (KMO) value was 0.846, indicating satisfactory sampling adequacy, while Bartlett's Test of Sphericity was significant (χ^2 = 1,486.372, $p < 0.001$), confirming the suitability of the data for factor analysis.

The three extracted factors accounted for 74.68% of the total variance, indicating a strong factor structure. All retained items demonstrated factor loadings above the recommended threshold of 0.50, confirming acceptable construct validity and alignment with the proposed conceptual framework. The results suggest that the identified critical success factors adequately represent the dimensions influencing IoT integration within sustainable agricultural supply chains.

4.2 Exploratory Factor Analysis for IoT Integration and End-to-End Value Creation

A second EFA was performed to examine the dimensionality of IoT Integration and End-to-End Value Creation constructs. The KMO statistic was 0.821, while Bartlett's Test of Sphericity was significant ($\chi^2 = 1{,}123.418$, $p < 0.001$), indicating that the data were suitable for factor analysis.

Two distinct components emerged: IoT Integration and End-to-End Value Creation. These factors explained 71.42% of the total variance. All measurement items recorded factor loadings above 0.50, indicating satisfactory construct validity. The findings confirm that IoT integration and value creation are distinct but closely related constructs within sustainable agricultural supply chains.

4.3 Reliability Analysis

Reliability analysis was conducted using Cronbach's Alpha to assess the internal consistency of the measurement scales. The results indicated satisfactory reliability for all constructs, with values exceeding the recommended threshold of 0.70 (Nunnally & Bernstein, 1994). The reliability analysis was conducted using Cronbach's Alpha to evaluate the internal consistency of the measurement scales. The results indicated that all constructs achieved reliability values above the recommended threshold of 0.70, demonstrating strong internal consistency and reliability. Specifically, Data Analytics Capability recorded a Cronbach's Alpha value of 0.91, indicating excellent reliability. Stakeholder Collaboration achieved a value of 0.88, reflecting a high level of internal consistency among the measurement items. Similarly, IoT Integration demonstrated excellent reliability with a Cronbach's Alpha value of 0.93, while End-to-End Value Creation recorded a value of 0.90, indicating strong reliability. These findings confirm that the measurement instrument is reliable and suitable for subsequent statistical analyses, including correlation and regression analyses. These findings demonstrate that the measurement instrument possesses strong internal consistency and is suitable for subsequent statistical analyses.

4.4 Regression Analysis and Hypothesis Testing

Multiple Regression Analysis was employed to examine the influence of Technological Infrastructure, Data Analytics Capability, and Stakeholder Collaboration on IoT Integration in Sustainable Agricultural Supply Chains. The overall regression model was statistically significant ($F = 56.842$, $p < 0.001$) and explained 71.2% of the variance in IoT Integration ($R^2 = 0.712$).

Among the independent variables, Data Analytics Capability emerged as the strongest predictor of IoT Integration ($\beta = 0.48$, $p < 0.001$), followed by Technological Infrastructure ($\beta = 0.37$, $p < 0.001$) and Stakeholder Collaboration ($\beta = 0.29$, $p < 0.01$). These findings indicate that organizations with strong analytical capabilities, robust technological infrastructure, and collaborative stakeholder networks are more likely to achieve successful IoT integration.

A second regression analysis was conducted to assess the effect of IoT Integration on End-to-End Value Creation. The model was statistically significant ($F = 62.317$, $p < 0.001$), explaining 68.9% of the variance in End-to-End Value Creation ($R^2 = 0.689$). IoT Integration demonstrated a strong positive influence on value creation outcomes ($\beta = 0.76$, $p < 0.001$).

The findings indicate that successful IoT integration contributes significantly to operational efficiency, supply chain visibility, resource optimization, sustainability performance, and overall value creation throughout the agricultural supply chain.

DISCUSSION OF FINDINGS

The findings of this study highlight the critical role of technological and organizational factors in facilitating successful IoT integration within sustainable agricultural supply chains. Consistent with previous studies on digital transformation and smart agriculture, the results demonstrate that Technological Infrastructure, Data Analytics Capability, and Stakeholder Collaboration significantly influence the effectiveness of IoT implementation.

Data Analytics Capability emerged as the most influential predictor of IoT Integration. This finding suggests that organizations capable of collecting, processing, and analyzing real-time data are better positioned to leverage IoT technologies for decision-making, operational optimization, and sustainability improvements. Effective data analytics enables stakeholders to monitor agricultural processes, anticipate disruptions, and respond proactively to changing market and environmental conditions.

Technological Infrastructure also exhibited a significant positive influence on IoT Integration. Reliable connectivity, interoperable systems, and scalable digital platforms are essential for supporting real-time communication and information exchange across agricultural supply chain networks. Without adequate infrastructure, organizations may face challenges in implementing and maximizing the benefits of IoT technologies.

Stakeholder Collaboration was found to be another important determinant of IoT Integration. The results indicate that effective communication, information sharing, and coordinated decision-making among farmers, suppliers, distributors, retailers, and technology providers contribute significantly to successful technology adoption. Collaborative relationships facilitate knowledge exchange and enhance supply chain transparency, ultimately supporting sustainability objectives.

Furthermore, the study confirmed a strong positive relationship between IoT Integration and End-to-End Value Creation. Organizations that effectively integrate IoT technologies across supply chain operations are more likely to achieve improvements in productivity, traceability, resource efficiency, customer satisfaction, and sustainability performance. These outcomes support the notion that IoT serves as a strategic enabler of value creation across the entire agricultural supply chain, from production to final consumption.

In conclusion, the findings validate the importance of critical success factors in achieving successful IoT integration and demonstrate the substantial contribution of IoT technologies to sustainable value creation. The study provides practical implications for policymakers, agricultural practitioners, supply chain managers, and technology providers seeking to enhance digital transformation initiatives and strengthen the sustainability and competitiveness of agricultural supply chains.

CONCLUSION

This study concludes that the successful integration of Internet of Things (IoT) technologies plays a crucial and strategic role in enhancing the sustainability, efficiency, and competitiveness of agricultural supply chains. The findings demonstrate that critical success factors, namely Technological Infrastructure, Data Analytics Capability, and Stakeholder Collaboration, significantly influence the effectiveness of IoT integration and contribute to end-to-end value creation across the agricultural supply chain. The integration of IoT technologies enables real-time monitoring, improved traceability, enhanced decision-making, and optimized resource utilization, supporting the transition toward more sustainable agricultural practices.

The research provides strong empirical evidence that Data Analytics Capability is one of the most influential factors affecting IoT integration. Organizations capable of effectively collecting, processing, and analyzing data generated by IoT devices are better positioned to improve operational performance, respond to supply chain disruptions, and make informed strategic decisions. Similarly, robust Technological Infrastructure provides the foundation necessary for seamless connectivity, data exchange, and system interoperability, ensuring the successful deployment and operation of IoT-enabled solutions throughout the supply chain.

Furthermore, the study highlights the importance of Stakeholder Collaboration in facilitating IoT integration within sustainable agricultural supply chains. Effective collaboration among farmers, suppliers, logistics providers, distributors, retailers, and technology providers enhances information sharing, supply chain visibility, and coordinated decision-making. Such collaborative relationships not only improve operational efficiency but also strengthen supply chain resilience and sustainability performance. The findings suggest that organizations adopting a collaborative approach are more likely to maximize the benefits derived from IoT technologies.

The study also confirms that successful IoT integration contributes significantly to End-to-End Value Creation. By enabling transparency, efficiency, traceability, and sustainability across supply chain activities, IoT technologies create value for multiple stakeholders throughout the agricultural ecosystem. Improvements in productivity, product quality, customer satisfaction, waste reduction, and resource optimization collectively contribute to sustainable economic and environmental outcomes. These findings support the growing recognition of IoT as a key enabler of digital transformation and sustainable development within the agricultural sector.

In the Malaysian context, the findings align with national initiatives promoting smart agriculture, digital transformation, and food security. As Malaysia continues to strengthen its agricultural sector through technological innovation, the successful integration of IoT technologies can support the achievement of sustainability goals while enhancing the competitiveness of agricultural supply chains. Policymakers, industry practitioners, and technology providers should therefore prioritize investments in digital infrastructure, analytics capabilities, and collaborative platforms to accelerate IoT adoption and maximize value creation.

From a practical perspective, the study suggests that agricultural organizations should focus on developing technological readiness, strengthening data management capabilities, and fostering collaborative networks among supply chain stakeholders. Capacity-building programs, digital literacy initiatives, and investment in IoT infrastructure can further support successful implementation efforts. Additionally, organizations should establish integrated data-sharing mechanisms and governance structures to facilitate seamless communication and coordination across the supply chain.

Future research should expand this study by investigating additional factors influencing IoT integration, such as organizational readiness, cybersecurity, regulatory support, and financial investment. Longitudinal studies could provide deeper insights into how IoT integration evolves and its long-term impact on sustainability performance and value creation. Furthermore, adopting advanced analytical techniques such as Structural Equation Modelling (SEM) may provide a more comprehensive understanding of the direct, indirect, mediating, and moderating relationships among the study variables.

In conclusion, IoT integration is not merely a technological advancement but a strategic enabler of sustainable agricultural supply chain transformation. By strengthening technological infrastructure, enhancing data analytics capabilities, and promoting stakeholder collaboration, agricultural organizations can successfully leverage IoT technologies to achieve end-to-end value creation, improve sustainability performance, and support long-term agricultural development.

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