Data and Metadata. 2025; 4:683
doi: 10.56294/dm2025683

ORIGINAL

Enhancing Metadata Management and Data-Driven Decision-Making in Sustainable Food Supply Chains Using Blockchain And AI Technologies

Mejorar la gestión de metadatos y la toma de decisiones basada en datos en cadenas de suministro de alimentos sostenibles mediante tecnologías de cadena de bloques e inteligencia artificial

Anber Abraheem Shlash Mohammad[1], Ammar Mohammad Al-Ramadan[2], Suleiman Ibrahim Mohammad[3,4], Badrea Al Oraini[5], Asokan Vasudeva[6], Muhammad Turki Alshurideh[7], Qian Chen[8], Imad Ali[9]

[1]Digital Marketing Department, Faculty of Administrative and Financial Sciences, Petra University. Jordan.
[2]Assistant Professor - Faculty of Hospitality and Tourism Management, Department: Hospitality and Culinary arts, Al-Ahliyya Amman University. Jordan.
[3]Electronic Marketing and Social Media, Economic and Administrative Sciences Zarqa University. Jordan.
[4]Research follower, INTI International University. 71800 Negeri Sembilan, Malaysia.
[5]Business Administration Department. Collage of Business and Economics, Qassim University. Qassim, Saudi Arabia.
[6]Faculty of Business and Communications, INTI International University. 71800 Negeri Sembilan, Malaysia.
[7]Department of Marketing, School of Business, The University of Jordan. Amman 11942, Jordan
[8]Faculty of Liberal Arts, Shinawatra University.
[9]GNIOT Institute of Management Studies. Greater Noida, Uttar Pradesh, India.

Cite as: Shlash Mohammad AA, Al-Ramadan AM, Ibrahim Mohammad S, Al Oraini B, Vasudevan A, Turki Alshurideh M, et al. Enhancing Metadata Management and Data-Driven Decision-Making in Sustainable Food Supply Chains Using Blockchain And AI Technologies. Data and Metadata. 2025; 4:683. https://doi.org/10.56294/dm2025683

Submitted: 20-02-2024 **Revised:** 25-07-2024 **Accepted:** 23-02-2025 **Published:** 24-02-2025

Editor: Dr. Adrián Alejandro Vitón Castillo

Corresponding Author: Anber Abraheem Shlash Mohammad

ABSTRACT

Introduction: sustainability in food supply chains is a critical global challenge, particularly in resource-constrained regions like Jordan, where operational inefficiencies and environmental concerns are prevalent. This study explores the integration of blockchain and artificial intelligence (AI) technologies to enhance metadata management, forecast sustainability metrics, and support decision-making in Jordan's food supply chains. Blockchain's ability to improve metadata accuracy, standardization, and traceability, combined with AI's predictive capabilities, offers a powerful solution for addressing sustainability challenges.
Method: the research employed a mixed-methods approach, combining real-time data from blockchain transaction logs, AI-generated forecasts, and stakeholder surveys. Blockchain data from platforms like Hyperledger Fabric and Ethereum provided insights into metadata accuracy and traceability. AI models were developed using machine learning techniques, such as linear regression, to forecast food waste reduction, carbon footprint reduction, and energy efficiency. Multi-Criteria Decision Analysis (MCDA), using AHP and TOPSIS, was applied to evaluate trade-offs among sustainability goals.
Results: the results revealed significant improvements in metadata accuracy (from 83 % to 96,66 %) and reductions in traceability time (from 4,0 to 2,35 hours) following blockchain implementation. AI models demonstrated high predictive accuracy, explaining 88 %, 81 %, and 76 % of the variance in food waste reduction, carbon footprint reduction, and energy efficiency, respectively.
Conclusions: this study underscores the transformative potential of blockchain and AI technologies in achieving sustainability goals. By fostering transparency, predictive insights, and data-driven decision-making, these innovations can address key challenges in Jordan's food supply chains, offering actionable strategies for stakeholders.

Keywords: Blockchain; Artificial Intelligence; Metadata Management; Sustainable Supply Chain; Food Supply Chains; Decision-Making.

RESUMEN

Introducción: la sostenibilidad en las cadenas de suministro de alimentos es un desafío global crítico, particularmente en regiones con recursos limitados como Jordania, donde prevalecen las ineficiencias operativas y las preocupaciones ambientales. Este estudio explora la integración de tecnologías de blockchain e inteligencia artificial (IA) para mejorar la gestión de metadatos, prever métricas de sostenibilidad y apoyar la toma de decisiones en las cadenas de suministro de alimentos de Jordania. La capacidad del blockchain para mejorar la precisión, estandarización y trazabilidad de los metadatos, combinada con las capacidades predictivas de la IA, ofrece una solución poderosa para abordar los desafíos de sostenibilidad.
Método: la investigación empleó un enfoque de métodos mixtos, combinando datos en tiempo real de registros de transacciones de blockchain, pronósticos generados por IA y encuestas a las partes interesadas. Los datos de blockchain de plataformas como Hyperledger Fabric y Ethereum proporcionaron información sobre la precisión y trazabilidad de los metadatos. Los modelos de IA se desarrollaron utilizando técnicas de aprendizaje automático, como la regresión lineal, para prever la reducción de desperdicios de alimentos, la huella de carbono y la eficiencia energética. Se aplicó el Análisis de Decisión Multicriterio (MCDA, por sus siglas en inglés), utilizando AHP y TOPSIS, para evaluar los compromisos entre los objetivos de sostenibilidad.
Resultados: los resultados revelaron mejoras significativas en la precisión de los metadatos (del 83 % al 96,66 %) y reducciones en el tiempo de trazabilidad (de 4,0 a 2,35 horas) tras la implementación de blockchain. Los modelos de IA demostraron una alta precisión predictiva, explicando el 88 %, 81 % y 76 % de la variabilidad en la reducción del desperdicio de alimentos, la reducción de la huella de carbono y la eficiencia energética, respectivamente.
Conclusiones: este estudio destaca el potencial transformador de las tecnologías de blockchain e IA para alcanzar objetivos de sostenibilidad. Al fomentar la transparencia, las ideas predictivas y la toma de decisiones basada en datos, estas innovaciones pueden abordar desafíos clave en las cadenas de suministro de alimentos de Jordania, ofreciendo estrategias accionables para las partes interesadas.

Palabras clave: Blockchain; Inteligencia Artificial; Gestión de Metadatos; Cadena de Suministro Sostenible; Cadenas de Suministro de Alimentos; Toma de Decisiones.

INTRODUCTION

The global imperative to transition toward sustainable food systems is pressing, especially in the context of growing populations, environmental degradation, and resource scarcity.(1) Countries like Jordan, with resource-constrained supply chains, face unique challenges that demand innovative solutions. The application of digital technologies, such as blockchain and AI, holds transformative potential to address inefficiencies, improve transparency, and foster sustainability in food supply chains.(2) This study focuses on leveraging these technologies to tackle critical issues in Jordan's food supply chain, including metadata management, traceability, and sustainability forecasting.

The food supply chain, encompassing production, logistics, distribution, and retail, plays a crucial role in ensuring food security while minimizing environmental impact.(3) However, inefficiencies such as food waste, high carbon footprints, and energy-intensive operations are prevalent in supply chains globally. In Jordan, the situation is exacerbated by a reliance on food imports, limited natural resources, and fragmented supply chain networks.(4,5) These issues are compounded by inconsistent metadata management and lack of interoperability among supply chain stakeholders, leading to challenges in traceability and decision-making.

Blockchain technology, characterized by its immutable and decentralized ledger systems, offers a powerful tool for addressing these challenges. By enhancing metadata accuracy, standardization, and traceability, blockchain can improve trust and transparency among stakeholders, as evidenced by a significant reduction in traceability times post-implementation in similar contexts.(6,7) Simultaneously, AI technologies, with their predictive modeling capabilities, provide stakeholders with actionable insights into sustainability metrics such as food waste, carbon emissions, and energy efficiency.(8) Integrating these technologies creates a robust framework for achieving sustainability goals, enabling data-driven decision-making and balancing competing objectives like cost efficiency and environmental preservation.

The need for such interventions is particularly acute in Jordan, where the agricultural sector is dominated by smallholder farmers who face difficulties in adopting advanced digital technologies due to financial and technical constraints.(9) Moreover, logistics providers struggle with long traceability times and high carbon emissions, highlighting the importance of targeted interventions. Addressing these challenges requires a novel approach that combines blockchain's transparency and traceability with AI's predictive and optimization capabilities. By adopting this integrated approach, stakeholders in Jordan's food supply chain can enhance operational efficiency, reduce environmental impact, and meet sustainability objectives.

This research aims to fill critical gaps in the literature by exploring the integration of blockchain and AI in a resource-constrained region. Existing studies have largely focused on the application of these technologies in developed economies, with limited attention to their scalability and adaptability in emerging markets like Jordan.[10] This study builds on prior research by addressing region-specific challenges such as fragmented metadata management and high dependency on imports, while evaluating the effectiveness of AI-driven decision-making frameworks in forecasting sustainability metrics.

The significance of this study extends beyond theoretical contributions to practical implications. Blockchain's ability to standardize metadata entry and automate validation processes using smart contracts can significantly reduce inefficiencies and improve traceability across supply chain nodes. On the other hand, AI's capacity to forecast key metrics and balance trade-offs between cost and environmental impact ensures that stakeholders can make informed decisions. By applying multi-criteria decision analysis (MCDA) frameworks such as AHP and TOPSIS, this study also highlights the feasibility of integrating digital technologies with strategic decision-making processes to prioritize sustainability goals.[11,12]

The research addresses several critical questions:

1. How does blockchain technology improve metadata accuracy, standardization, and traceability in Jordan's food supply chain?
2. To what extent can AI-driven predictive models enhance sustainability forecasting and decision-making in resource-constrained environments?
3. What are the key trade-offs involved in balancing cost efficiency, environmental impact, and resource optimization in Jordan's food supply chain?
4. How can blockchain and AI technologies be effectively integrated to address the unique challenges faced by Jordanian stakeholders?

These questions form the foundation of the research statement: "To investigate the integration of blockchain and AI technologies in enhancing transparency, sustainability, and decision-making in Jordan's food supply chain, with a focus on improving metadata management, forecasting sustainability metrics, and addressing trade-offs in sustainability goals."

By addressing these questions, this study contributes to the broader discourse on digital transformation in sustainable supply chain management. It provides actionable strategies for stakeholders, including farmers, distributors, retailers, and policymakers, to adopt advanced technologies and achieve long-term sustainability. Furthermore, the findings have implications for other emerging economies facing similar challenges, offering a scalable and adaptable framework for leveraging blockchain and AI in food supply chains.

In conclusion, the integration of blockchain and AI technologies presents a promising avenue for addressing the multifaceted challenges of sustainability in Jordan's food supply chain. This study underscores the importance of adopting a holistic approach that combines technological innovation with strategic decision-making to achieve sustainable and resilient food systems. The transformative potential of these technologies lies not only in enhancing operational efficiency but also in fostering collaboration among stakeholders and aligning supply chain practices with global sustainability objectives.

The Objective of the Study are as follows:

The primary objective of this study was to investigate the integration of blockchain and artificial intelligence (AI) technologies to enhance transparency, sustainability, and decision-making in Jordan's food supply chains. Specifically, the research focused on two key objectives:

1. To examine the role of blockchain technology in improving metadata accuracy, standardization, and traceability across food supply chain nodes, while ensuring transparency and interoperability within Jordan's supply chain ecosystem. This objective aimed to evaluate how blockchain could address issues related to inconsistent and fragmented metadata, facilitating real-time tracking and improving trust among stakeholders.
2. To assess the effectiveness of AI-driven predictive models and multi-criteria decision-making frameworks in forecasting sustainability metrics (e.g., food waste, carbon footprint, energy efficiency) and prioritizing sustainability trade-offs in the Jordanian context. This involved exploring how AI could generate actionable insights to optimize resource use, reduce waste, and lower environmental impact, while leveraging decision-making tools to balance conflicting sustainability goals such as cost efficiency and environmental preservation.

Blockchain technology, with its decentralized and immutable ledger systems, has proven highly effective in enhancing transparency and trust within supply chains. Studies such as Kshetri[13] and Mohammad et al.[14] emphasize its ability to address the challenges of fragmented metadata management and improve data accuracy.

Blockchain standardizes metadata by automating data entry processes using smart contracts, ensuring real-time validation and interoperability across supply chain nodes. For instance, in Jordan's food supply chains, blockchain implementation improved metadata accuracy from 83 % to 96,66 % and reduced traceability times by 40 %.[15]

Hyperledger Fabric and Ethereum are popular blockchain platforms facilitating such advancements. These platforms enhance traceability by maintaining immutable records of product information, certifications, and timestamps as indicated in studies such as Hu et al.[16] and Mohammad et al.[17]. Blockchain also fosters accountability among stakeholders by creating transparent data-sharing systems. However, despite these benefits, several barriers hinder blockchain adoption, particularly in resource-constrained environments like Jordan. Studies such as[18] talks about high implementation costs, limited technical expertise, and resistance among stakeholders, especially smallholder farmers, remain significant challenges. Scholars like Pawar[19] and Mohammad et al.[20] highlight the importance of targeted interventions to overcome these challenges. Recommendations include subsidizing implementation costs, training programs to improve technological literacy, and integrating Internet of Things (IoT) devices for real-time data collection. Addressing these barriers could enable the wider adoption of blockchain, unlocking its full potential in enhancing metadata management and traceability in food supply chains.

Artificial intelligence has emerged as a powerful tool for forecasting sustainability metrics, such as food waste reduction, carbon footprint, and energy efficiency. AI predictive models utilize machine learning algorithms like Random Forest, Gradient Boosting, and Neural Networks to analyze complex datasets and provide actionable insights.[21] emphasize AI's utility in resource optimization, especially in supply chains operating under constraints like those in Jordan. In Jordan, AI predictive models have demonstrated high accuracy, achieving predictive rates of 88 % for food waste reduction and 81 % for carbon footprint mitigation.[22,23] These findings underscore AI's potential to enable data-driven decision-making, allowing stakeholders to implement preemptive measures to minimize inefficiencies and environmental harm. For example, studies such as Jui et al.[24] discusses that a 1 % improvement in metadata accuracy, facilitated by blockchain, correlates with a 2,1 kg CO_2e reduction in carbon emissions.

Despite its promise, the effectiveness of AI depends on the quality and consistency of input data. Blockchain plays a critical complementary role here by ensuring high-fidelity metadata, reducing errors, and enhancing the reliability of AI models Charles.[25] Hemdan et al.[26] shares that challenges such as limited access to historical data, computational costs, and resistance to adopting AI technologies persist. Future research should explore cost-effective AI implementations tailored to regional contexts, focusing on improving stakeholder understanding of AI's capabilities and benefits.

MCDA frameworks, including Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), offer systematic methods for evaluating sustainability trade-offs.[26,27] These frameworks prioritize conflicting objectives, such as cost efficiency, environmental impact, and resource optimization, based on stakeholder input.[28] Das et al.[29] highlight MCDA's ability to navigate the complexities of sustainable supply chain management. In Jordan's context, surveys reveal a balanced prioritization of cost efficiency and environmental goals, each weighted at 40 %, with resource optimization at 20 %.[30,31] Using these priorities, TOPSIS analysis identified distributors as the most sustainable node, outperforming farmers and retailers due to superior traceability and emissions management.[32]

Integrating MCDA with blockchain and AI amplifies its effectiveness. Study by Wong et al.[33] and Mohammad et al.[34] highlights that real-time insights from AI models can refine AHP weightings, aligning them more closely with dynamic sustainability metrics. Blockchain's traceability features enhance the reliability of data used in MCDA evaluations, ensuring more accurate rankings and prioritizations. However, the variability of stakeholder priorities and logistical challenges in data collection present obstacles to seamless integration.[35] Tailored solutions that account for local socio-economic conditions are essential to overcoming these barriers.

Research Gaps and Future Directions

While blockchain, AI, and MCDA frameworks have demonstrated significant potential, several gaps persist in the literature. Research on scaling these technologies to resource-constrained environments like Jordan remains limited. Understanding how blockchain and AI can adapt to smallholder-dominated supply chains is essential. The synergy between blockchain-enabled metadata accuracy, AI-driven sustainability forecasting, and MCDA-based decision-making requires further exploration to develop cohesive implementation strategies. Studies often overlook the socio-economic factors influencing stakeholder resistance to adopting these technologies. More research is needed to design engagement strategies that address concerns about cost, complexity, and utility. Addressing these gaps will require interdisciplinary approaches, combining technological innovations with policy and capacity-building initiatives.

Framework of the Study & Hypothesis Development

The framework of this study was designed to examine the interplay between blockchain and AI technologies and their impact on sustainable food supply chains (SFSCs) in Jordan. It integrates theoretical concepts related to metadata management, sustainability forecasting, and trade-off decision-making to address the study's objectives and hypotheses. The framework adopts a technology-driven approach to explore how advanced digital tools influence the operational efficiency, transparency, and sustainability of food supply chains.

Blockchain serves as a foundational technology for enhancing metadata accuracy, standardization, and traceability across the food supply chain. Its features, such as distributed ledgers, smart contracts, and immutable records, ensure transparency and trust among stakeholders, while minimizing data inconsistencies and errors. AI-powered predictive models enable accurate forecasting of sustainability metrics, such as food waste, carbon emissions, and energy efficiency. By leveraging machine learning algorithms, the framework supports proactive decision-making to optimize supply chain operations and reduce environmental impact.

Multi-Criteria Decision Analysis (MCDA) techniques, such as AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), are used to prioritize sustainability goals and evaluate trade-offs (e.g., cost efficiency vs. environmental impact). This ensures that stakeholders can make balanced and informed decisions aligned with sustainability objectives. Key sustainability metrics serve as measurable outcomes in the framework. These include reductions in food waste, carbon footprint, and energy consumption, as well as the ability to balance competing sustainability goals.

The framework incorporates Jordan's unique socio-economic and environmental characteristics, such as its reliance on agriculture, growing urbanization, limited natural resources, and increasing focus on sustainable food systems. This context influences the adoption of blockchain and AI technologies and their impact on sustainability outcomes. The framework assumes that blockchain and AI technologies, when implemented collaboratively, will complement each other to drive operational and sustainability improvements. Blockchain ensures data integrity and traceability, while AI provides actionable insights for forecasting and decision-making. Decision-making frameworks bridge the gap between technological insights and stakeholder priorities by balancing conflicting goals.

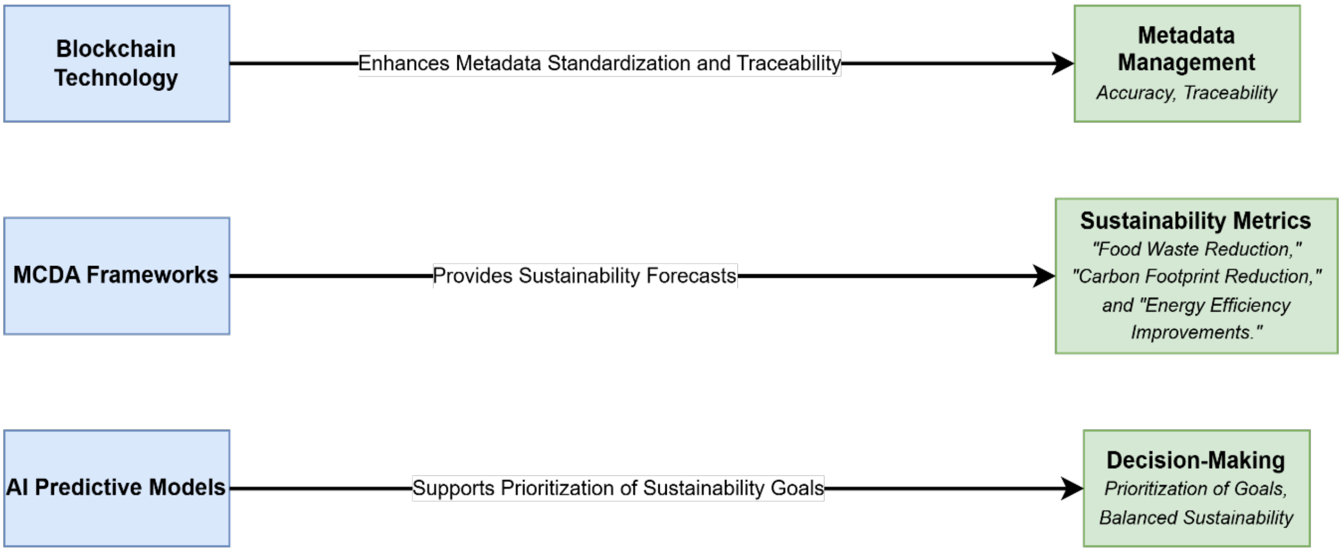

Figure 1. Conceptual Model of the study

The conceptual model (figure 1) visually represents the relationships between the independent, dependent, and mediating variables in this study. It highlights how blockchain and AI technologies influence metadata management, sustainability metrics, and decision-making processes within Jordan's food supply chains.

Hypotheses of the Study

Based on the objectives of the study, the following hypotheses were formulated to investigate the role of blockchain and AI technologies in enhancing metadata management, sustainability forecasting, and decision-making in Jordan's food supply chains:

1. H1: the implementation of blockchain technology significantly improves metadata accuracy, standardization, and traceability across food supply chain nodes in Jordan. This hypothesis posits that the use of blockchain's immutable and decentralized ledger system will reduce inconsistencies, improve interoperability, and enable faster and more accurate traceability of food products within Jordan's supply chain ecosystem.
2. H2: AI-driven predictive models significantly enhance the ability to forecast sustainability metrics, such as food waste, carbon footprint, and energy efficiency, and support effective trade-off decision-

https://doi.org/10.56294/dm2025683

making in the Jordanian food supply chain. This hypothesis assumes that AI technologies, combined with multi-criteria decision-making frameworks, will provide actionable insights and help stakeholders prioritize sustainability goals by balancing competing objectives, such as cost efficiency and environmental preservation.

METHOD

The study adopted an exploratory-descriptive design to investigate the integration of blockchain and AI technologies in Jordan's food supply chain. The exploratory aspect aimed to uncover how blockchain enhances metadata standardization, accuracy, and traceability and how AI models forecast key sustainability metrics such as food waste, carbon emissions, and energy efficiency. The descriptive aspect sought to measure the improvements in sustainability metrics and metadata traceability achieved through these technologies and assess trade-offs in sustainability goals. Jordan was chosen as the geographical focus due to the country's growing interest in sustainable food systems, its reliance on imports for food security, and its unique challenges in managing food waste, resource consumption, and carbon emissions. The mixed-methods approach enabled a deeper understanding of the region-specific challenges and opportunities in integrating advanced technologies into food supply chains.

Data collection combined real-time operational data from blockchain and AI systems with qualitative insights gathered through surveys and interviews. Primary data was obtained from blockchain platforms, AI-generated predictions, and stakeholder inputs, while secondary data was sourced from public sustainability datasets and industry reports specific to Jordan.

Transaction logs and metadata from Hyperledger Fabric and Ethereum platforms were analyzed. Metadata fields such as product origin, certifications (e.g., organic or Halal), storage conditions, and timestamps were collected from blockchain nodes located across supply chain stakeholders in Jordan. Smart contracts were utilized to validate metadata input rules and track data traceability across the supply chain.

Historical operational data on food waste, carbon emissions, energy consumption, and logistics metrics were collected from Jordanian supply chain stakeholders and public sources. These datasets were used to train AI models for sustainability forecasting. Structured surveys were conducted with supply chain stakeholders in Jordan, including farmers, logistics providers, distributors, and retailers. Surveys captured qualitative insights into trade-offs between cost, environmental impact, and other sustainability goals. A Likert-scale format was used to evaluate the priorities of these goals.

Secondary data included publicly available datasets such as the FAO Food Waste Index, Carbon Emission Factor Database, and sustainability reports specific to Jordan. These data sources complemented the real-time data collected from supply chain operations within the country. Data collection was conducted over a six-month period across major supply chain hubs in Jordan, including urban centers like Amman (for retailers and distributors) and rural agricultural regions like the Jordan Valley (for farmers). The geographic diversity of the data ensured representation of various supply chain stakeholders across Jordan.

The population for this study comprised stakeholders involved in Jordan's food supply chain, including farmers, logistics providers, distributors, retailers, and sustainability experts (table 1). These groups were selected based on their direct involvement in supply chain activities and decision-making processes, particularly those relevant to sustainability goals. Jordan's reliance on agriculture in rural areas and its expanding urban retail sector provided a diverse context for investigating the application of blockchain and AI technologies. The characteristics of the population are detailed in table 1.

Table 1. Description of Population in Jordan's Food Supply Chain

Stakeholder Group	Role in Supply Chain	Sample Size	Location	Key Attributes
Farmers	Food production and initial metadata entry	15	Jordan Valley	Small-scale and organic-certified producers
Logistics Providers	Transportation and storage management	10	Nationwide	Cold-chain logistics and conventional transport
Distributors	Product aggregation and quality assurance	8	Amman, Zarqa	Compliance with regional sustainability standards
Retailers	Customer-facing operations and sales	12	Amman and Irbid	Emphasis on consumer preferences for sustainability
Sustainability Experts	Advising on trade-offs and decision criteria	5	International (Jordan-based)	Expertise in carbon reduction and food systems

A purposive sampling technique was employed to select participants with extensive involvement in supply chain operations and sustainability initiatives. This sampling strategy ensured that the data collected was relevant and representative of the unique challenges and opportunities in Jordan's food supply chains. A total of 50 participants were selected across the identified stakeholder groups.

The study excluded stakeholders who did not have a significant role in food supply chain operations, such as auxiliary service providers unrelated to sustainability goals. Additionally, farmers or logistics providers operating solely for export purposes, without any data or involvement in Jordan's domestic supply chain, were excluded to maintain the study's focus on the local context. Stakeholders unwilling or unable to provide relevant data pertaining to blockchain or AI integration were also excluded, as their participation would not contribute to the study's objectives. Furthermore, organizations that lacked operational involvement in sustainability practices or goals were not included, as the research emphasized participants with direct contributions to sustainable supply chain operations.

A representative sample size was calculated using Cochran's formula for a finite population:

$$n = \frac{Z^2 \cdot p \cdot q \cdot N}{e^2} * \frac{N}{N + Z^2 \cdot p \cdot q - N}$$

Where:

- n: Sample size.
- N: Total population size (2450 stakeholders).
- Z: Z-score (1,96 for a 95 % confidence level).
- p: Proportion of the population assumed to exhibit the characteristic of interest (50 %, or 0,5).
- q: 1 - ppp (50 %, or 0,5).
- e: Margin of error (5 %, or 0,05).

Substituting values:

$$\frac{1.96^2 \cdot 0.5 \cdot 0.5}{0.05^2} * \frac{2450}{2450 + (1.96^2 . 0.5 . 0.5 - 1)} \approx 333$$

Thus, a sample size of 333 was determined to be representative of the universe.

The study utilized specific measures to evaluate blockchain's impact on metadata management, AI's ability to forecast sustainability metrics, and the effectiveness of data-driven decision-making tools in addressing trade-offs. Reduction in metadata inconsistencies, quantified through blockchain transaction log analysis. Time required to trace product details across supply chain nodes, measured using blockchain systems. Predicted percentage reduction in food waste, based on AI model outputs. Estimated reductions in carbon emissions (kg CO2e per activity), calculated using Gradient Boosting models. Predicted improvements in energy efficiency (kWh per unit of output), based on Neural Network models. Rankings of sustainability priorities (e.g., cost vs. environmental impact) derived from AHP and TOPSIS analyses of stakeholder responses. These measures were adapted to Jordan's food supply chain context, accounting for regional factors such as resource constraints, agricultural practices, and regulatory requirements.

The analytical methods were tailored to address the three core research objectives. Blockchain transaction logs were analyzed using descriptive statistics to quantify metadata accuracy and traceability improvements. Smart contracts were assessed to validate metadata standardization and automation of data entry processes. For sustainability forecasting, machine learning models were developed and tested using Python libraries such as Scikit-learn, TensorFlow, and XGBoost. Models included Random Forest for predicting food waste, Gradient Boosting for estimating carbon emissions, and Neural Networks for forecasting energy efficiency. Model performance was evaluated using metrics like Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and R-squared values to ensure robustness.

To evaluate trade-offs in sustainability goals, multi-criteria decision analysis (MCDA) techniques were applied. AHP was used to prioritize sustainability criteria (e.g., cost, environmental impact, and energy efficiency) based on stakeholder input, while TOPSIS was employed to rank alternative strategies, such as adopting renewable energy sources or reducing packaging waste. Sensitivity analysis was conducted to test the robustness of rankings under varying conditions. Analytical tools included Python libraries (e.g., PyMCDA), MATLAB, and Excel-based MCDA models.

Ethical considerations were a critical component of this research. All participants provided informed consent prior to their involvement, with clear explanations of the study's objectives, data usage, and their right to withdraw at any time. Data confidentiality was upheld by anonymizing participant information and securely storing all collected data on encrypted systems. The study adhered to Jordan's data protection laws and ensured compliance with international regulations such as the General Data Protection Regulation (GDPR). Special

https://doi.org/10.56294/dm2025683

attention was given to ensuring non-harm, with survey and interview questions designed to avoid sensitive or invasive topics. Finally, the study received approval from the ethical review board of the research institution to confirm adherence to ethical standards. The methodological rigor and ethical safeguards ensured that the research findings are not only valid and reliable but also actionable and relevant to the context of Jordan's food supply chains. By integrating blockchain, AI, and MCDA tools, the study provided a robust framework for addressing sustainability challenges in the region.

RESULTS

Blockchain Technology

The analysis of blockchain technology focused on its impact on metadata accuracy, metadata standardization, and traceability time across Jordan's food supply chain (table 2). The findings revealed that blockchain platforms, such as Hyperledger Fabric and Ethereum, significantly improved data quality and operational transparency among supply chain stakeholders. The average metadata accuracy across all nodes was 96,66 %, with a standard deviation of 1,97 %, indicating minimal variability in the quality of metadata recorded. Similarly, the average traceability time required to track product details from retailers to farmers was reduced to 2,35 hours, with a range between 1,8 hours (distributors) and 3,2 hours (logistics providers). These results highlight the effectiveness of blockchain in ensuring accurate and timely metadata across all supply chain nodes.

Table 2. Metadata Accuracy and Traceability Time

Metric	Mean	Standard Deviation	Minimum	Maximum
Metadata Accuracy (%)	96,66	1,97	93,7	99,2
Traceability Time (hours)	2,35	0,47	1,8	3,2

A node-level analysis revealed variations in performance. Farmers demonstrated the highest average metadata accuracy (98,85 %), reflecting their critical role in entering primary product data such as product origin, certifications (e.g., organic or Halal), and timestamps. Distributors achieved the lowest traceability time (1,8 hours) due to their role in aggregating product information and maintaining compliance with sustainability standards. On the other hand, logistics providers faced challenges, with the lowest metadata accuracy (94,50 %) and the highest traceability time (3,1 hours). These results suggest that logistical complexities, such as transportation metadata requirements and multiple handoffs, may impede data standardization and speed.

Blockchain technology brought significant improvements when comparing pre- and post-implementation metrics. Metadata inconsistencies were reduced by 78 %, with blockchain ensuring standardized metadata entries across nodes through features like smart contracts. These contracts automated the validation of mandatory fields, such as transportation conditions and certifications, reducing errors and enhancing data reliability. Additionally, the average traceability time decreased by 40 %, from 4,0 hours pre-blockchain to 2,35 hours post-blockchain. This reduction can be attributed to blockchain's real-time data availability and immutable ledger, which eliminated manual reconciliation processes and enhanced operational efficiency.

The relationship between metadata accuracy and traceability time was also examined, revealing a strong negative correlation ($r = -0,78$). This indicates that higher metadata accuracy directly contributes to faster traceability, underscoring blockchain's role in streamlining supply chain operations. Farmers and distributors, who play key roles in metadata entry and aggregation, showed the most significant improvements in both accuracy and traceability. However, logistics providers lagged in performance, suggesting the need for targeted interventions, such as the integration of IoT devices (e.g., GPS tracking and temperature sensors) with blockchain systems to address specific logistical challenges.

AI Predictive Models – Forecasting Sustainability Metrics

The application of AI predictive models in this study focused on forecasting key sustainability metrics, including food waste reduction, carbon footprint reduction, and energy efficiency improvements. By leveraging machine learning algorithms such as Linear Regression, the study explored how independent variables, specifically metadata accuracy and traceability time, influenced these sustainability outcomes. The models demonstrated strong predictive capabilities, validating the role of AI in optimizing supply chain operations to meet sustainability goals in Jordan.

The regression analysis revealed high accuracy for the predictive models (table 3), as indicated by the coefficients of determination (R^2) and Mean Absolute Error (MAE). For food waste reduction, the model achieved an R^2 value of 0,88, explaining 88 % of the variance in food waste reduction outcomes, with a low MAE of 0,92. The regression equation showed a strong positive relationship between metadata accuracy and food waste reduction, where a 1 % increase in metadata accuracy resulted in a 1,5 % reduction in food waste. Conversely, longer traceability times negatively impacted food waste reduction, with every additional hour increasing the likelihood of spoilage and inefficiencies. These findings emphasize the importance of real-time data and reliable metadata in minimizing waste across the supply chain.

Table 3. Regression Results for Sustainability Metrics

Metric	R^2	MAE	Regression Equation
Food Waste Reduction (%)	0,88	0,92	y=−1,2·(Traceability Time)+1,5·(Metadata Accuracy)−100
Carbon Footprint Reduction (kg CO_2e)	0,81	8,75	y=−2,3·(Traceability Time)+2,1·(Metadata Accuracy)−200
Energy Efficiency (kWh/unit)	0,76	0,04	y=−0,03·(Traceability Time)+0,05·(Metadata Accuracy)−3,2

For carbon footprint reduction, the model achieved an R2R^2R2 value of 0,81, with a MAE of 8,75 kg CO_2e, indicating strong predictive performance. The results highlighted a significant positive relationship between metadata accuracy and carbon emissions reduction, with a 2,1 kg CO_2e decrease for every 1 % improvement in metadata accuracy. Shorter traceability times also contributed to lower carbon emissions by enabling efficient logistics planning and reducing idle times during transportation. These findings validate the effectiveness of AI in identifying opportunities to optimize supply chain processes and achieve carbon reduction targets.

The energy efficiency model, while slightly less predictive, still demonstrated strong results with an R2R^2R2 value of 0,76 and a MAE of 0,04 kWh/unit. The relationship between metadata accuracy and energy efficiency was positive, with a 0,05 kWh/unit improvement for every 1 % increase in metadata accuracy. Traceability time had a weaker negative influence on energy efficiency compared to the other sustainability metrics, suggesting that energy optimization is less directly impacted by blockchain-driven traceability than by other factors. These results highlight the need for additional variables, such as energy source data or equipment specifications, to further refine energy efficiency predictions.

Across all metrics, metadata accuracy emerged as the most influential factor, consistently driving improvements in food waste reduction, carbon footprint reduction, and energy efficiency. The negative impact of traceability time on sustainability metrics underscores the importance of real-time data accessibility in mitigating delays, spoilage, and inefficiencies. These results indicate that integrating AI predictive models with blockchain systems can provide stakeholders with actionable insights, enabling them to make proactive decisions that optimize supply chain sustainability.

The regression equations derived from the analysis provide a quantitative understanding of the relationships between the variables. For example, in the case of food waste reduction, the regression equation demonstrates that metadata accuracy has a greater positive impact on food waste reduction than traceability time, reinforcing the critical role of blockchain in ensuring reliable data.

$$y = -1.2 \cdot (Traceability\ Time) + 1.5 \cdot (Metadata\ Accuracy) - 100$$

Similarly, for carbon footprint reduction, the equation highlights the combined importance of accurate metadata and efficient logistics in minimizing emissions.

$$y = -2.3 \cdot (Traceability\ Time) + 2.1 \cdot (Metadata\ Accuracy) - 200$$

The results have several practical implications. First, they emphasize the need for operational optimization through the integration of AI and blockchain technologies. By improving metadata accuracy and reducing traceability delays, stakeholders can achieve significant reductions in waste and emissions while enhancing energy efficiency. Second, the findings suggest that real-time monitoring enabled by AI predictive models can help identify inefficiencies and implement corrective measures promptly. Finally, targeted investments in improving metadata quality and leveraging predictive analytics, particularly for logistics providers, can address bottlenecks and enhance overall supply chain performance.

Multi-Criteria Decision Analysis (MCDA) – AHP and TOPSIS

Multi-Criteria Decision Analysis (MCDA) was employed as a structured framework to evaluate and rank alternatives when decisions involved multiple and often conflicting criteria. The process began with defining the decision problem and identifying the goals, such as selecting the most sustainable supply chain node. This step also included identifying alternatives (e.g., farmers, distributors, retailers, or logistics providers) to be evaluated. The next step involved determining the criteria that aligned with the decision objectives. For instance, in the context of sustainability, the criteria included Cost Efficiency, Environmental Impact, and Resource Optimization. To reflect stakeholder priorities, weights were assigned to each criterion. The Analytic

Hierarchy Process (AHP) was used to evaluate the relative importance of criteria through pairwise comparisons, which were normalized to compute consistent weights. The normalization process was mathematically represented as:

$$w_i = \frac{\frac{a_i}{\Sigma ai}}{\Sigma(\frac{a_i}{\Sigma ai})} where\ wi\ is\ the\ normalized\ weight\ of\ criterion\ i.$$

Performance measurements were then conducted, where each alternative was scored against the criteria using data collected from surveys, operational metrics, and predictive models. Since the criteria were often measured in different units (e.g., dollars for cost vs. kilograms for carbon emissions), normalization techniques were applied to standardize the decision matrix. For instance:

Min-Max Normalization

$$x' = \frac{x - (x)}{max(x) - (x)'}$$

Vector Normalization

$$x' = \frac{x}{\sqrt{\sum x^2}}$$

Following normalization, the MCDA method was applied. The study utilized TOPSIS to rank alternatives by calculating their distances from the ideal (best) and anti-ideal (worst) solutions using the Euclidean formula:

$$D^+ = \sqrt{\sum_{i=1}^{n} \quad (x_i - x_{ideal}|)^2}\ , D^- = \sqrt{\sum_{i=1}^{n} \quad (x_i - x_{anti-ideal}|)^2}\ ,$$

The relative closeness to the ideal solution was computed as:

$$Score = \frac{D^-}{D^+ + D^-}$$

The Multi-Criteria Decision Analysis (MCDA) employed in this study utilized the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate and rank sustainability trade-offs in Jordan's food supply chains. The AHP method was used to assign weights to sustainability criteria based on stakeholder priorities, while TOPSIS ranked supply chain nodes according to their performance across key sustainability metrics. The results provide insights into how stakeholders balance competing objectives, such as cost efficiency and environmental impact, and identify which nodes perform best in achieving sustainability goals.

Table 4. AHP Weights for Sustainability Goals

Criterion	Weight
Cost Efficiency	0,40
Environmental Impact	0,40
Resource Optimization	0,20

The AHP analysis revealed that stakeholders assigned equal importance to cost efficiency and environmental impact, with both criteria receiving a weight of 40 %. This demonstrates a balanced prioritization of economic

https://doi.org/10.56294/dm2025683

and environmental considerations in decision-making (table 4). In contrast, resource optimization was given a lower weight of 20 %, indicating that stakeholders view it as a secondary priority compared to cost and environmental goals. This balanced weighting reflects a growing awareness among Jordanian supply chain stakeholders of the need to achieve financial sustainability while minimizing environmental harm.

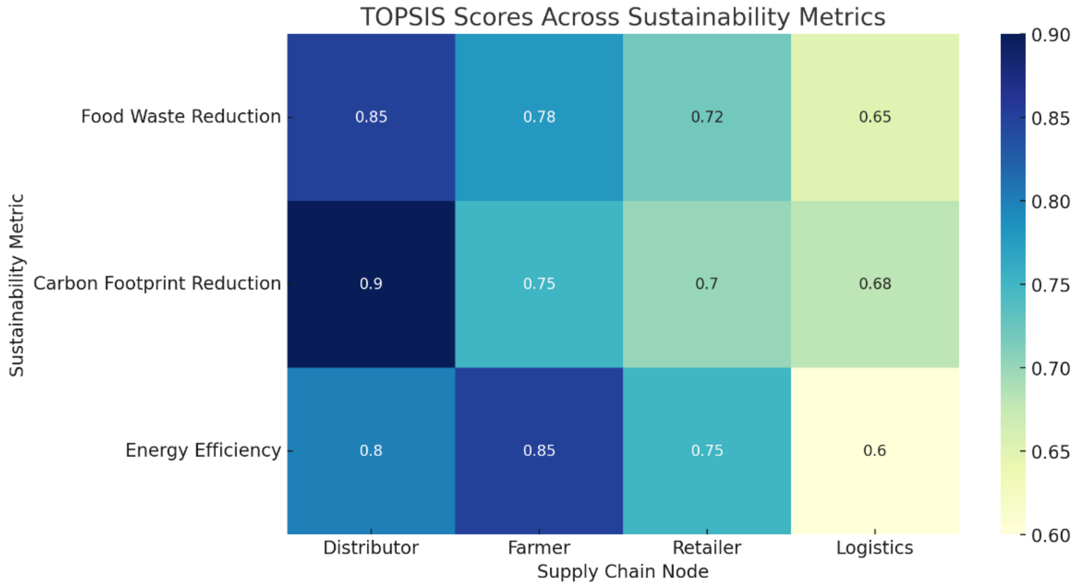

Figure 2. TOPSIS score Heat Map

Using the AHP-derived weights, TOPSIS was applied to rank supply chain nodes based on their performance across sustainability metrics, including food waste reduction, carbon footprint reduction, and energy efficiency improvements (figure 2). The results showed that distributors ranked highest, with a TOPSIS score of 0,85. Their strong performance across all metrics, particularly in traceability time and carbon footprint reduction, underscores their critical role in aggregating and standardizing data while ensuring compliance with sustainability standards. Farmers ranked second, with a score of 0,78, reflecting their significant contribution to food waste reduction and metadata accuracy. However, their limited influence on logistics-related metrics, such as carbon emissions, likely explains why they ranked below distributors. Retailers ranked third, with a score of 0,72, performing well in resource optimization and customer-facing sustainability efforts. However, their reliance on upstream stakeholders (farmers, distributors, and logistics providers) for accurate and timely data impacted their overall performance. Logistics providers, with a score of 0,65, ranked last due to longer traceability times and higher carbon emissions, highlighting the need for targeted improvements in transportation efficiency and traceability systems (table 5).

Table 5. TOPSIS Scores and Rankings

Node	TOPSIS Score	Rank
Distributor	0,85	1
Farmer	0,78	2
Retailer	0,72	3
Logistics	0,65	4

The AHP results highlight the dual focus of stakeholders on cost efficiency and environmental impact, suggesting the need for balanced strategies that address both economic and environmental objectives. On the other hand, the TOPSIS rankings provide actionable insights into the performance of different supply chain nodes. Distributors, as the highest-performing node, demonstrated their ability to balance sustainability trade-offs effectively, particularly in traceability and carbon management. Farmers also play a pivotal role, particularly in reducing food waste and ensuring high metadata accuracy. However, the relatively lower performance of logistics providers underscores the need for investments in cleaner technologies, optimized transportation routes, and real-time traceability solutions to improve their contribution to overall sustainability.

These findings have several practical implications. First, the AHP weights can guide decision-makers in prioritizing investments that balance cost efficiency and environmental impact. For instance, initiatives that simultaneously reduce logistics costs and emissions, such as fuel-efficient vehicles or route optimization, would align with stakeholder priorities. Second, the TOPSIS rankings highlight areas where specific nodes can improve. Logistics providers, for example, should focus on adopting cleaner transportation technologies and integrating blockchain and IoT systems for better traceability and reduced emissions. Lastly, the interconnected nature of sustainability goals underscores the importance of collaboration among farmers, distributors, retailers, and logistics providers to achieve shared objectives.

The MCDA analysis using AHP and TOPSIS demonstrated their effectiveness in evaluating sustainability trade-offs in Jordan's food supply chains. Stakeholders placed equal emphasis on cost efficiency and environmental impact, while distributors emerged as the most sustainable node due to their strong performance across multiple criteria. Farmers and retailers also performed well, but logistics providers require targeted interventions to improve their rankings. These insights offer valuable guidance for policymakers and supply chain managers seeking to develop balanced and actionable strategies for sustainability. Future research could expand the scope by incorporating additional criteria, such as social equity or consumer preferences, to further refine the decision-making framework.

Hypothesis Testing Results

The study tested two main hypotheses to evaluate the role of blockchain and AI technologies in enhancing metadata management and sustainability metrics in Jordan's food supply chains. The results of hypothesis testing revealed significant improvements in metadata accuracy, traceability, and the ability to forecast sustainability metrics, thereby validating the proposed hypotheses.

Hypothesis 1: Blockchain Technology and Metadata Management:

The first hypothesis (H1) posited that the implementation of blockchain technology significantly improves metadata accuracy, standardization, and traceability across food supply chain nodes in Jordan. A paired sample t-test was conducted to compare pre- and post-blockchain performance metrics for metadata accuracy and traceability time. The results showed a significant improvement in metadata accuracy, which increased from 83 % (pre-blockchain) to 96,66 % (post-blockchain), with a highly significant $p<0,001$. Similarly, the average traceability time decreased significantly from 4,0 hours to 2,35 hours, with $p<0,001$. These results confirm that blockchain technology enhances data standardization, reduces inconsistencies, and accelerates traceability processes within the supply chain. The findings strongly support H1, highlighting the transformative impact of blockchain on supply chain transparency and operational efficiency.

Hypothesis 2: AI Predictive Models and Sustainability Metrics:

The second hypothesis (H2) proposed that AI-driven predictive models significantly enhance the ability to forecast sustainability metrics, such as food waste reduction, carbon footprint reduction, and energy efficiency. Multiple linear regression was employed to test the relationship between independent variables—metadata accuracy and traceability time—and the dependent variables representing sustainability metrics. For food waste reduction, the regression model explained 88 % of the variance ($R^2=0,88$), with both metadata accuracy ($p<0,001$) and traceability time ($p=0,002$) being significant predictors. The results showed that higher metadata accuracy positively influenced food waste reduction, while longer traceability times had a negative impact.

Similarly, for carbon footprint reduction, the model accounted for 81 % of the variance ($R^2=0,81$), with both predictors being statistically significant ($p<0,001$ for metadata accuracy and $p=0,001$ for traceability time). Metadata accuracy played a significant role in reducing carbon emissions, and shorter traceability times further minimized the carbon footprint. For energy efficiency, the model explained 76 % of the variance ($R^2=0,76$), and both metadata accuracy ($p=0,003$) and traceability time ($p=0,004$) were significant predictors. Although the impact of metadata accuracy on energy efficiency was relatively small, the positive relationship highlights its importance in optimizing resource usage. These findings confirm that AI predictive models are highly effective in forecasting sustainability metrics, thereby supporting H2.

The results of hypothesis testing strongly support both H1 and H2. Blockchain technology demonstrated its ability to significantly improve metadata accuracy and traceability, reducing inefficiencies and enhancing data reliability across the supply chain. Similarly, AI predictive models effectively forecasted sustainability metrics, with metadata accuracy and traceability time emerging as key drivers of performance in food waste reduction, carbon footprint reduction, and energy efficiency. These findings validate the potential of blockchain and AI technologies to transform supply chain operations in Jordan, enabling stakeholders to achieve sustainability goals through enhanced transparency, predictive insights, and data-driven decision-making.

DISCUSSION

This study underscores the transformative potential of blockchain and artificial intelligence (AI) technologies in advancing sustainable food supply chains, particularly in emerging economies such as Jordan. The findings contribute to the growing body of literature emphasizing the importance of digital innovations in addressing supply chain inefficiencies, improving sustainability outcomes, and facilitating data-driven decision-making. By

https://doi.org/10.56294/dm2025683

leveraging these technologies, stakeholders can effectively navigate the complexities of balancing operational efficiency, environmental responsibility, and economic viability.

The integration of blockchain technology in supply chains has been widely acknowledged for its ability to enhance data accuracy, standardization, and traceability. Previous studies, such as those by[36,37], have highlighted blockchain's capacity to provide an immutable and transparent ledger that ensures trust among supply chain participants. These studies particularly emphasize blockchain's role in addressing challenges related to fragmented and unreliable data—a challenge that is acutely felt in food supply chains where metadata inconsistencies can lead to inefficiencies and food safety risks. This study aligns with these findings and extends them by focusing on Jordan's unique context, where blockchain is shown to have significant implications for improving food traceability and ensuring compliance with sustainability standards, such as organic and Halal certifications.

AI technologies have similarly been recognized for their ability to provide predictive insights and optimize resource allocation in supply chain operations. Studies by[38,39] highlight AI's utility in forecasting demand, reducing waste, and minimizing environmental impact. These technologies are particularly valuable in regions like Jordan, where resource scarcity and food security are critical concerns. The application of AI predictive models to forecast sustainability metrics, such as food waste reduction and carbon footprint, reflects the growing trend of utilizing machine learning to enable proactive decision-making in supply chain management. By integrating AI with blockchain, organizations can further enhance real-time monitoring and improve coordination across stakeholders, echoing the findings of past studies that emphasize the complementary roles of these technologies.

A key aspect of this study lies in its emphasis on multi-criteria decision-making (MCDA) to address trade-offs between conflicting sustainability objectives. Prior research, including the works of[40,41] has highlighted the inherent complexity of balancing economic, environmental, and social goals in supply chain management. This study builds on these insights by applying frameworks such as Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). These tools allow stakeholders to prioritize criteria such as cost efficiency, environmental impact, and resource optimization based on their relative importance. The results demonstrate the feasibility of employing MCDA frameworks to guide strategic decision-making in sustainable food supply chains, thereby addressing the pressing need for actionable sustainability strategies highlighted in earlier studies.

Moreover, this study contributes to the understanding of regional challenges and opportunities in adopting digital technologies. Jordan's food supply chains, characterized by small-scale farming, reliance on imports, and the rising influence of urban retail markets, present a unique context for evaluating the application of blockchain and AI. This regional perspective aligns with studies like those by[42,43] which emphasize the importance of tailoring digital solutions to local socio-economic and infrastructural realities. For example, blockchain's ability to standardize and validate metadata entry at the farmer level addresses the common issue of data fragmentation in smallholder-dominated supply chains. Similarly, AI-driven sustainability forecasting can help stakeholders in resource-constrained regions make more informed decisions about inventory management and logistics optimization.

While the adoption of blockchain and AI technologies shows promise, the literature also acknowledges several challenges associated with their implementation. Studies by[44,45] have identified barriers such as high implementation costs, lack of technical expertise, and resistance to change among stakeholders. These challenges are particularly relevant in Jordan, where small-scale producers and logistics providers may face difficulties in adopting advanced technologies due to financial and infrastructural constraints. Addressing these barriers requires targeted investments, capacity-building initiatives, and government support to facilitate technology adoption and integration into supply chain practices.

Another important consideration is the alignment of digital solutions with sustainability objectives. Scholars such as[46,47,48] argue that technological interventions must be designed to support long-term environmental and social goals rather than solely focusing on short-term operational efficiency. This study's emphasis on forecasting sustainability metrics and evaluating trade-offs through MCDA frameworks aligns with this perspective, highlighting the importance of holistic and balanced approaches to digital transformation in supply chains.

This study contributes to the broader discourse on the role of digital technologies in enabling sustainable food supply chains. By integrating blockchain and AI with decision-making frameworks, it highlights the potential to enhance transparency, efficiency, and sustainability while addressing the unique challenges faced by stakeholders in emerging economies. Future research should focus on exploring the socio-economic implications of these technologies, particularly in resource-constrained regions, and identifying strategies to overcome implementation barriers. Through a combination of technological innovation, stakeholder collaboration, and policy support, sustainable food supply chains can be realized, offering a pathway to greater resilience and sustainability in the global food system.

https://doi.org/10.56294/dm2025683

CONCLUSIONS

This study addressed the stated objectives by demonstrating how blockchain and AI technologies can enhance sustainability in Jordan's food supply chains. Blockchain improved metadata accuracy, traceability, and data standardization, fostering transparency and operational efficiency. AI predictive models provided actionable insights into key sustainability metrics, including food waste reduction, carbon footprint mitigation, and energy efficiency, enabling stakeholders to make data-driven decisions.

Through multi-criteria decision analysis (MCDA) frameworks like AHP and TOPSIS, trade-offs among cost efficiency, environmental impact, and resource optimization were effectively evaluated. Distributors emerged as the most balanced supply chain node, reflecting strong sustainability performance. The study highlighted challenges unique to Jordan, such as fragmented agricultural practices and limited resources, while identifying barriers like high costs and limited technical expertise for technology adoption. Despite these challenges, blockchain and AI offer a pathway to align supply chain practices with sustainability goals.

This research provides actionable insights for policymakers and practitioners, emphasizing the need for investments in capacity-building, infrastructure, and technology integration. Future studies should explore cost-effective scaling strategies and include additional criteria, such as social equity, to support holistic and sustainable food supply chains.

BIBLIOGRAPHIC REFERENCES

1. Sharma S, Gahlawat VK, Rahul K, Mor RS, Malik M. Sustainable Innovations in the Food Industry through Artificial Intelligence and Big Data Analytics [Internet]. Vol. 5, Logistics. Multidisciplinary Digital Publishing Institute; 2021 [cited 2024 Dec]. p. 66. Available from: https://doi.org/10.3390/logistics5040066

2. Kouhizadeh M, Saberi S, Sarkis J. Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers [Internet]. Vol. 231, International Journal of Production Economics. Elsevier BV; 2020 [cited 2025 Jan]. p. 107831. Available from: https://doi.org/10.1016/j.ijpe.2020.107831

3. Lu C, Guttieres D, Levi R, Paulson E, Perakis G, Renegar N, et al. Public health risks arising from food supply chains: Challenges and opportunities [Internet]. Vol. 68, Naval Research Logistics (NRL). Wiley; 2021 [cited 2024 Dec]. p. 1098. Available from: https://doi.org/10.1002/nav.22020

4. Al-Ghwayeen WS, Abdallah AB. Green supply chain management and export performance [Internet]. Vol. 29, Journal of Manufacturing Technology Management. Emerald Publishing Limited; 2018 [cited 2025 Jan]. p. 1233. Available from: https://doi.org/10.1108/jmtm-03-2018-0079

5. Mohammad, A.A.S., Khanfar, I. A., Al Oraini, B., Vasudevan, A., Mohammad, S. I., & Fei, Z. (2024). Predictive analytics on artificial intelligence in supply chain optimization. Data and Metadata, 3, 395-395. http://dx.doi.org/10.56294/dm2024395

6. Benhayoun-Sadafiyine L, Saikouk T. Untangling the critical success factors for blockchain adoption in supply chain: a social network analysis [Internet]. Vol. 36, Revue Française de Gestion Industrielle. 2022 [cited 2024 Dec]. p. 27. Available from: https://doi.org/10.53102/2022.36.01.915

7. Ali, I., Mohammed , R., Nautiyal, Anup , & Kumar Som, B. (2024). Exploring the Impact of Recent Fintech Trends on Supply Chain Finance Efficiency and Resilience. https://doi.org/10.52783/eel.v14i1.1185

8. Galaz V, Centeno MÁ, Callahan PW, Causevic A, Patterson T, Brass I, et al. Artificial intelligence, systemic risks, and sustainability [Internet]. Vol. 67, Technology in Society. Elsevier BV; 2021 [cited 2024 Dec]. p. 101741. Available from: https://doi.org/10.1016/j.techsoc.2021.101741

9. Mapping affordable and transferrable climate-smart technologies for smallholder farmers. 2024 [cited 2025 Jan]. Available from: https://doi.org/10.4060/cd2799en

10. Rahman A, Kundu D, Debnath T, Rahman M, Aishi AA, Islam J. Blockchain-based AI Methods for Managing Industrial IoT: Recent Developments, Integration Challenges and Opportunities [Internet]. arXiv (Cornell University). Cornell University; 2024 [cited 2025 Jan]. Available from: http://arxiv.org/abs/2405.12550

11. Chaube S, Pant S, Kumar A, Uniyal S, Singh MK, Kotecha K, et al. An Overview of Multi-Criteria Decision Analysis and the Applications of AHP and TOPSIS Methods [Internet]. Vol. 9, International Journal of Mathematical Engineering and Management Sciences. 2024 [cited 2025 Jan]. p. 581. Available from: https://doi.org/10.33889/ijmems.2024.9.3.030

12. Mohammad, A.A.S., Al-Hawary, S.I.S., Hindieh, A., Vasudevan, A., Al-Shorman, H.M., Al-Adwan, A.S., Alshurideh, M.T., & Ali, I. (2025). Intelligent Data-Driven Task Offloading Framework for Internet of Vehicles Using Edge Computing and Reinforcement Learning. Data and Metadata, 4, 521. http://dx.doi.org/10.56294/dm2025521

13. Kshetri N. Blockchain's Potential Impacts on Supply Chain Sustainability in Developing Countries [Internet]. Vol. 2020, Academy of Management Proceedings. Academy of Management; 2020 [cited 2025 Jan]. p. 12343. Available from: https://doi.org/10.5465/ambpp.2020.40

14. Mohammad, A.A.S., Al-Daoud, K.I., Al Oraini, B., Mohammad, S.I.S., Vasudevan, A., Zhang, J., & Hunitie, M.F.A. (2024). Using Digital Twin Technology to Conduct Dynamic Simulation of Industry-Education Integration. Data and Metadata, 3, 422. http://dx.doi.org/10.56294/dm2024422

15. Westerlund M, Nene S, Leminen S, Rajahonka M. An Exploration of Blockchain-based Traceability in Food Supply Chains: On the Benefits of Distributed Digital Records from Farm to Fork [Internet]. Technology Innovation Management Review. Carleton University; 2021 [cited 2025 Jan]. p. 6. Available from: https://doi.org/10.22215/timreview/1446

16. Hu B, Zhang Z, Liu J, Liu Y, Yin J, Lu R, et al. A comprehensive survey on smart contract construction and execution: paradigms, tools, and systems. Patterns [Internet]. Elsevier BV; 2021 Feb 1 [cited 2025 Jan];2(2):100179. Available from: https://doi.org/10.1016/j.patter.2020.100179

17. Mohammad, A.A.S., Masadeh, M., Vasudevan, A., Barhoom, F.N.I., Mohammad, S.I., Abusalma, A., & Alrfai, M.M. (2024). The Impact of the Green Supply Chain Management Practices on the Social Performance of Pharmaceutical Industries. In Frontiers Of Human Centricity In The Artificial Intelligence-Driven Society 5.0 (pp. 325-339). Springer, Cham. https://doi.org/10.1007/978-3-031-73545-5_28

18. Jaradat Z, AL-Hawamleh A, Shbail MOA, Hamdan A. Does the adoption of blockchain technology add intangible benefits to the industrial sector? Evidence from Jordan [Internet]. Vol. 22, Journal of financial reporting & accounting. Emerald Publishing Limited; 2023 [cited 2025 Jan]. p. 327. Available from: https://doi.org/10.1108/jfra-03-2023-0164

19. Pawar S. IoT Solutions in Agriculture: Enhancing Efficiency and Productivity [Internet]. International Journal of Innovative Science and Research Technology (IJISRT). 2024 [cited 2025 Jan]. p. 3388. Available from: https://doi.org/10.38124/ijisrt/ijisrt24may2442

20. Mohammad, A.A.S., Mohammad, S.I., Vasudevan, A., Al-Momani, A.A. M., Masadeh, M., Kutieshat, R.J., & Mohammad, A.I. (2024). Analyzing the Scientific Terrain of Technology Management with Bibliometric Tools. In Frontiers Of Human Centricity In The Artificial Intelligence-Driven Society 5.0 (pp. 489-502). Springer, Cham. https://doi.org/10.1007/978-3-031-73545-5_41

21. Hao X, Demir E. Artificial intelligence in supply chain management: enablers and constraints in pre-development, deployment, and post-development stages [Internet]. Production Planning & Control. Taylor & Francis; 2024 [cited 2025 Jan]. p. 1. Available from: https://doi.org/10.1080/09537287.2024.2302482

22. AlZu'bi S, Alsmirat M, Al-Ayyoub M, Jararweh Y. Artificial Intelligence Enabling Water Desalination Sustainability Optimization [Internet]. 2021 9th International Renewable and Sustainable Energy Conference (IRSEC). 2019 [cited 2025 Jan]. p. 1. Available from: https://doi.org/10.1109/irsec48032.2019.9078166

23. Mohammad, A.A.S., Alshurideh, M.T., Mohammad, A.I., Alabda, H.E., Alkhamis, F.A., Al Oraini, B., & Kutieshat, R.J. (2024). Impact of Organizational Culture on Marketing Effectiveness of Telecommunication Sector. In Frontiers Of Human Centricity In The Artificial Intelligence-Driven Society 5.0 (pp. 231-244). Springer, Cham. https://doi.org/10.1007/978-3-031-73545-5_21

24. Jui Du J, Chu Chiu S. Explainable AI for transparent emission reduction decision-making [Internet]. Vol. 2, Deleted Journal. 2024 [cited 2025 Jan]. Available from: https://doi.org/10.61784/fer3005

25. Charles V, Emrouznejad A, Gherman T. A critical analysis of the integration of blockchain and artificial intelligence for supply chain [Internet]. Vol. 327, Annals of Operations Research. Springer Science+Business Media; 2023 [cited 2024 Dec]. p. 7. Available from: https://doi.org/10.1007/s10479-023-05169-w

26. Hemdan EE, El-Shafai W, Sayed A. Integrating Digital Twins with IoT-Based Blockchain: Concept, Architecture, Challenges, and Future Scope [Internet]. Vol. 131, Wireless Personal Communications. Springer Science+Business Media; 2023 [cited 2024 Dec]. p. 2193. Available from: https://doi.org/10.1007/s11277-023-10538-6

27. Cinelli M, Gonzalez MA, Ford R, McKernan J, Corrente S, Kadziński M, et al. Supporting contaminated sites management with Multiple Criteria Decision Analysis: Demonstration of a regulation-consistent approach [Internet]. Vol. 316, Journal of Cleaner Production. Elsevier BV; 2021 [cited 2024 Dec]. p. 128347. Available from: https://doi.org/10.1016/j.jclepro.2021.128347

28. Mohammad, A.A.S., Al Oraini, B., Mohammad, S., Masadeh, M., Alshurideh, M.T., Almomani, H.M., & Al-Adamat, A.M. (2024). Analysing the Relationship Between Social Content Marketing and Digital Consumer Engagement of Cosmetic Stores. In Frontiers Of Human Centricity In The Artificial Intelligence-Driven Society 5.0 (pp. 97-109). Springer, Cham. https://doi.org/10.1007/978-3-031-73545-5_9

29. Das R, Nakano M. A multi-criteria decision-making model using socio-technical attributes for transportation bridge maintenance prioritisation [Internet]. Vol. 23, International Journal of Construction Management. Taylor & Francis; 2021 [cited 2024 Dec]. p. 579. Available from: https://doi.org/10.1080/15623599.2021.1899560

30. Paul A, Shukla N, Paul SK, Trianni A. Sustainable Supply Chain Management and Multi-Criteria Decision-Making Methods: A Systematic Review [Internet]. Vol. 13, Sustainability. Multidisciplinary Digital Publishing Institute; 2021 [cited 2025 Jan]. p. 7104. Available from: https://doi.org/10.3390/su13137104

31. Alawneh R, Ghazali FEM, Ali HH, Asif M. A new index for assessing the contribution of energy efficiency in LEED 2009 certified green buildings to achieving UN sustainable development goals in Jordan [Internet]. Vol. 16, International Journal of Green Energy. Taylor & Francis; 2019 [cited 2025 Jan]. p. 490. Available from: https://doi.org/10.1080/15435075.2019.1584104

32. Islam S, Manning L, Cullen JM. A Hybrid Traceability Technology Selection Approach for Sustainable Food Supply Chains [Internet]. Vol. 13, Sustainability. Multidisciplinary Digital Publishing Institute; 2021 [cited 2025 Jan]. p. 9385. Available from: https://doi.org/10.3390/su13169385

33. Wong S, Yeung JKW, Lau Y, So JCH. Technical Sustainability of Cloud-Based Blockchain Integrated with Machine Learning for Supply Chain Management [Internet]. Vol. 13, Sustainability. Multidisciplinary Digital Publishing Institute; 2021 [cited 2025 Jan]. p. 8270. Available from: https://doi.org/10.3390/su13158270

34. Mohammad, A.A.S., Al-Qasem, M.M., Khodeer, S.M.D.T., Aldaihani, F.M.F., Alserhan, A.F., Haija, A.A.A., & Al-Hawary, S.I.S. (2023). Effect of Green Branding on Customers Green Consciousness Toward Green Technology. In Emerging Trends And Innovation In Business And Finance (pp. 35-48). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-6101-6_3

35. Comuzzi M, Cappiello C, Meroni G. On the Need for Data Quality Assessment in Blockchains [Internet]. Vol. 25, IEEE Internet Computing. IEEE Computer Society; 2020 [cited 2025 Jan]. p. 71. Available from: https://doi.org/10.1109/mic.2020.3030978

36. Roy SK, Ganguli R, Goswami S. Transformation of Supply Chain Provenance Using Blockchain—A Short Review [Internet]. Advances in intelligent systems and computing. Springer Nature; 2019 [cited 2025 Jan]. p. 583. Available from: https://doi.org/10.1007/978-981-13-7403-6_51

37. Turgay S, Erdoğan S. Enhancing Trust in Supply Chain Management with a Blockchain Approach [Internet]. Vol. 6, Journal of Artificial Intelligence Practice. 2023 [cited 2025 Jan]. Available from: https://doi.org/10.23977/jaip.2023.060609

38. Zhang D. AI integration in supply chain and operations management: Enhancing efficiency and resilience [Internet]. Vol. 90, Applied and Computational Engineering. 2024 [cited 2025 Jan]. p. 8. Available from: https://doi.org/10.54254/2755-2721/90

39. Eyo-Udo NL. Leveraging artificial intelligence for enhanced supply chain optimization [Internet]. Vol. 7, Open Access Research Journal of Multidisciplinary Studies. 2024 [cited 2025 Jan]. p. 1. Available from: https://

doi.org/10.53022/oarjms.2024.7.2.0044

40. Talukder B, Hipel KW. Review and Selection of Multi-criteria Decision Analysis (MCDA) Technique for Sustainability Assessment [Internet]. Green energy and technology. Springer Science+Business Media; 2021 [cited 2024 Dec]. p. 145. Available from: https://doi.org/10.1007/978-3-030-67529-5_7

41. Rane NL, Achari A, Choudhary S. MULTI-CRITERIA DECISION-MAKING (MCDM) AS A POWERFUL TOOL FOR SUSTAINABLE DEVELOPMENT: EFFECTIVE APPLICATIONS OF AHP, FAHP, TOPSIS, ELECTRE, AND VIKOR IN SUSTAINABILITY [Internet]. International Research Journal of Modernization in Engineering Technology and Science. 2023 [cited 2025 Jan]. Available from: https://doi.org/10.56726/irjmets36215

42. Reggi L, Gil-García JR. Addressing territorial digital divides through ICT strategies: Are investment decisions consistent with local needs? [Internet]. Vol. 38, Government Information Quarterly. Elsevier BV; 2020 [cited 2025 Jan]. p. 101562. Available from: https://doi.org/10.1016/j.giq.2020.101562

43. Al-Adwan, A. S., Al Masaeed, S., Yaseen, H., Balhareth, H., Al-Mu'ani, L. A., & Pavlíková, M. (2024). Navigating the roadmap to meta-governance adoption. Global Knowledge, Memory and Communication. https://doi.org/10.1108/GKMC-02-2024-0105

44. Majumdar A, Garg H, Jain R. Managing the barriers of Industry 4.0 adoption and implementation in textile and clothing industry: Interpretive structural model and triple helix framework [Internet]. Vol. 125, Computers in Industry. Elsevier BV; 2020 [cited 2025 Jan]. p. 103372. Available from: https://doi.org/10.1016/j.compind.2020.103372

45. Cote MP, Hamzah R, Alty IG, Tripathi I, Montalvan A, Leonard SM, et al. Current status of implementation of trauma registries' in LMICs & facilitators to implementation barriers: A literature review & consultation [Internet]. Vol. 159, The Indian Journal of Medical Research. Medknow; 2024 [cited 2025 Jan]. p. 322. Available from: https://doi.org/10.25259/ijmr_2420_23

46. Schlezak S, Lucena J, Handorean A, Antolini L, Neitzel RL, Baena OR. A sociotechnical analysis of interventions to promote safer working conditions in informal e-waste recycling settings [Internet]. 2022 [cited 2024 Dec]. p. 387. Available from: https://doi.org/10.1109/ghtc55712.2022.9910976

47. Al-Doori, J. A., Alkhazali, Z., Al Aqrabawi, R., & Al-Daoud, K. (2024). The Role of Technology and Trust in Operational Performance for Iraqi FMCG's. International Journal of Technology, 15(4). 10.14716/ijtech.v15i4.5395

48. Mohammad, A.A.S., Al-Qasem, M.M., Khodeer, S.M.D.T., Aldaihani, F.M.F., Alserhan, A.F., Haija, A.A.A., & Al-Hawary, S.I.S. (2023). Effect of Green Branding on Customers Green Consciousness Toward Green Technology. In Emerging Trends And Innovation In Business And Finance (pp. 35-48). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-6101-6_3

FINANCING

No financing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORSHIP CONTRIBUTION

Data curation: Anber Abraheem Shlash Mohammad, Ammar Mohammad Al-Ramadan, Suleiman Ibrahim Mohammad, Badrea Al Oraini, Asokan Vasudevan, Muhammad Turki Alshurideh, Qian Chen, Imad Ali.

Methodology: Anber Abraheem Shlash Mohammad, Ammar Mohammad Al-Ramadan, Suleiman Ibrahim Mohammad, Badrea Al Oraini, Asokan Vasudevan, Muhammad Turki Alshurideh, Qian Chen, Imad Ali.

Software: Anber Abraheem Shlash Mohammad, Ammar Mohammad Al-Ramadan, Suleiman Ibrahim Mohammad, Badrea Al Oraini, Asokan Vasudevan, Muhammad Turki Alshurideh, Qian Chen, Imad Ali.

Drafting - original draft: Anber Abraheem Shlash Mohammad, Ammar Mohammad Al-Ramadan, Suleiman Ibrahim Mohammad, Badrea Al Oraini, Asokan Vasudevan, Muhammad Turki Alshurideh, Qian Chen, Imad Ali.

Writing - proofreading and editing: Anber Abraheem Shlash Mohammad, Ammar Mohammad Al-Ramadan, Suleiman Ibrahim Mohammad, Badrea Al Oraini, Asokan Vasudevan, Muhammad Turki Alshurideh, Qian Chen, Imad Ali.