Journal of Management Science Research Review
https://jmsrr.com/index.php/Journal/about
Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

From Blockchain to Green Outcomes: How Training and Supply Chain Learning Shape Sustainable Supply Chain Performance?

Gulzaib Jabbar
Karachi University Business School, University of Karachi, Pakistan, ORCID: https://orcid.org/0009-0001-4821-5401, Gulzaibjabbar28@gmail.com
Hammad Zafar
Karachi University Business School, University of Karachi, Pakistan.
ORCID: https://orcid.org/0009-0000-1067-1439,
hammad.zafar@uok.edu.pk
Sheikh Muhammad Fakhar E Alam Siddiqui
Assistant Professor, Karachi University Business School, University of Karachi, Pakistan, ORCID: https://orcid.org/0009-0000-1073-5623,
fakhrealam@uok.edu.pk

Abstract
The paper explores the role of the blockchain technology in improving the environmental performance in terms of sustainable supply chain performance as well as the moderating effects of training practices and supply chain learning. Although there is increased attention towards the future of digital sustainability, there is little empirical information on how blockchain can be converted into quantifiable environmental impacts and whether organizational competencies enhance the association. The design was done using a quantitative cross-sectional design based on the survey information of supply chain and operations professionals. Partial Least Squares Structural Equation Modeling (PLS-SEM) was used to test the conceptual model. The reliability and validity were established by using Cronbachs alpha, composite reliability, and AVE, and hypotheses and moderation effects were tested using bootstrapping. Findings indicate that blockchain technology plays a significant role in sustainable supply chain performance (β= 0.842, $p < 0.001$) which also plays an important role in enhancing environmental performance (β= 0.561, $p < 0.001$). The model accounts 70.8 percent and 71.2 percent of sustainable supply chain and environmental performance respectively. The moderation effects of training practices and supply chain learning were however insignificantly significant. The study is applicable to digital sustainability literature because it empirically proves that blockchain-mediated sustainability functions through the structured operation practice as opposed to conditional capability enhancement. The results provide theoretical purification and practical recommendations to incorporate blockchain into the environmental performance strategies.
Keywords: Blockchain Technology, Sustainable Supply Chain Performance, Environmental Performance, Training Practices, Supply Chain Learning, Digital Sustainability, PLS-SEM

Introduction

The fast spreading of Industry 4.0 technologies has had a fundamental impact on the supply chain organizations, decision processes, and sustainability plans in both manufacturing and services industries. Blockchain is one of such technologies that have the potential to improve the supply chain partners in terms of transparency, traceability, and trust (Dutta et al., 2024; Bag et al., 2023; Kache and Seuring, 2023). The recent empirical studies show that the adoption of blockchain decreases opportunistic behavior and enhances compliance and coordination in the complex supply chains (Dutta et al., 2024; Ivanov and Dolgui, 2024). With the pressure of sustainability increasing as a result of regulatory requirements and stakeholder demands, organizations are turning to digital technologies to facilitate green transformation programs (Ghadge et al., 2023; Bressanelli et al., 2023; Awan et al., 2023). Nevertheless, as technological investments are growing, the degree to which blockchain can be translated into real environmental change is yet to be developed on a theoretical level.

Digitalization, sustainability demands and geopolitical realignments are causing a radical change in the manufacturing and industrial supply chain sector. The use of Industry 4.0 technologies in industries of emerging and developed countries is becoming increasingly popular as one of the methods to increase the level of transparency, efficiency of work, and environmental safety (Bag et al., 2023; Ivanov and Dolgui, 2024; Ghadge et al., 2023; Kache and Seuring, 2023). This has been seen by widespread interest in the field of blockchain integration into the supply chain systems because of its capacity to establish immutable, transparent, and decentralized records of transactions, thus mitigating fraud, inefficiencies, and environmental misreporting (Dutta et al., 2024; Ivanov and Dolgui, 2024). The adoption of blockchain is being established in industries like manufacturing, logistics, and energy not only as a technological improvement but as a sustainability enabler that can help to make the corporate work compliant with the global environmental objectives (Bressanelli et al., 2023; Ghadge et al., 2023; Bag et al., 2023).

Research Questions

RQ1: In what ways does blockchain technology impact sustainable performance of supply chain systems in the industrial supply chain systems?

RQ2: How much sustainable supply chain performance acts as the mediator between blockchain technology and environmental performance?

RQ3: How training practices and learning on supply chain moderate's relationship between sustainable supply chain performance and environmental performance?

Objectives of the Study

- To investigate how blockchain technology can influence the performance of the sustainable supply chain in the industrial supply chain systems.

Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

- To examine the mediating position of sustainable supply chain performance in the correlation among blockchain technology and environmental performance.
- To examine the moderating impact of training practices on the linkage between sustainable supply chain performance and environmental performance.
- To determine the mediating role played by the learning of supply chain on the relationship between sustainable supply chain performance and environmental performance.

Literature Review

The blockchain technology has become a disruptive form of digital infrastructure in the supply chain ecosystems that allow decentralized data sharing, immutable recording of transactions, and enhanced transparency between the organizations. Recent studies emphasize that blockchain can enhance traceability, opportunistic behavior minimization, as well as partners trust in the supply chain (Saberi et al., 2023; Yadav et al., 2024; Kouhizadeh et al., 2024). Its use in the industrial environment helps track the products, carbon footprint, and environmental standards in real time, and thus makes operational performance meet the sustainability targets (Kamble et al., 2023; Dutta et al., 2024). The previous conceptual literature focused on the capacity of blockchain to remove information asymmetry and improve communication among fragmented supply networks (Kouhizadeh et al., 2024). Nevertheless, blockchain has already well-established technological possibilities, but its efficiency is heavily reliant upon the ways the organizations incorporate them into larger sustainability plans.

Theoretical Framework

Resource-Based View (RBV)

We have the Resource-Based View (RBV) as the main theoretical background of this work. According to RBV, value, rare, inimitable, and non-substitutable (VRIN) resources help firms to attain sustained competitive advantage (Awan et al., 2023; Bag et al., 2023). Digital technologies, in particular blockchain, are conceptualized in recent studies of the supply chain as strategic organizational resources that improve supply chain transparency, coordination, and operational efficiency (Bressanelli et al., 2023; Kamble et al., 2023). However, RBV notes that resources are not sufficient to ensure high performance unless they are successfully utilized by the organization process. Previous studies on sustainability also confirm that the internal capabilities are the cause of environmental performance and not just the adoption of technologies (Dutta et al., 2024; El Baz and Ruel, 2024). In the given study, the conceptualized blockchain technology is perceived as a strategic technological resource, and the sustainable supply chain performance is seen as the ability to convert the former into the environmental output.

Practice-Based View (PBV)

The Practice-Based View (PBV) builds on the RBV and claims that the deviations in the performance of the organizations are found in the unique operational practices and not solely in the resources (Bag et al., 2023;

Bressanelli et al., 2023). In the case of supply chains, sustainability practices, like green procurement, environmental monitoring, or eco-design, are some of the most important sources of performance variation (Helo, 2023; Ghadge et al., 2023). The latest blockchain literature indicates that digital systems are possible to improve performance only when they are a part of organized sustainability practices (Dutta et al., 2024; Luthra et al., 2023; Bag et al., 2023). PBV can thus offer the explanation of why sustainable supply chain performance is the mediating mechanism between blockchain technology and the environmental performance.

Unified Theory of Acceptance and Use of Technology (UTAUT)

The Unified Theory of Acceptance and Use of Technology (UTAUT) is a behavioral theory that suggests how organizations adopt and use technological systems (Kouhizadeh et al., 2024). Recent research on blockchain supply chain management integrates UTAUT to describe the adoption decisions and performance values (Queiroz et al., 2023; Sahebi et al., 2022; Yadav et al., 2024). UTAUT highlights performance expectancy, expectancy of effort, enabling conditions and social influence among other factors that influence the effectiveness of technology utilization. Previous research on digital transformation proves that the willingness of employees and the institutionalization of the changes are significant to achieving the benefits of the technology (Mukhopadhyay et al., 2024; Parmentola et al., 2022).

Purpose of the theoretical integration and study

This paper allows a comprehensive explanation of blockchain-driven environmental performance by combining RBV as the key theory with the supporting ones of PBV and UTAUT. RBV identifies blockchain as a strategic resource, PBV explains the mediation role of sustainable supply chain practices, and UTAUT states the relevance of training and learning as facilitating mechanisms that can increase the use of technology (Kouhizadeh et al., 2024; Zhang et al., 2025; Ren et al., 2023; Queiroz et al., 2023; Bag et al., 2023). This research aims to empirically test a moderate mediation model where blockchain technology enhances the performance of the environment by sustainable supply chain performance, and training practices and supply chain learning enforce the relationship. The overall goal is to enhance the literature on blockchain-sustainability by showing that environmental benefits are resource-based, practice facilitated, and behaviorally conditioned.

Supporting & Negating Views

A prevailing view in the current literature on the supply chain supports the case that blockchain technology has a positive impact on sustainable supply chain performance through supporting transparency, traceability, and coordination within a chain of supply networks. The recent research indicates that the blockchain-based systems minimize the information asymmetry and enhance the processes of green procurement and monitoring (Yadav et al., 2024; Zhang et al., 2025; Ren et al., 2023). In the perspective of the RBV, blockchain can be viewed as an important technological tool that can enhance sustainability potential when used properly (Kouhizadeh et al., 2024; Bag et al., 2023). Nonetheless, an alternative perspective states that the implementation of blockchain does not necessarily result in a better sustainable performance because it is expensive and has scale and organizational resistance (Saberi et al., 2023; Parmentola et al., 2022). Critics posit that until there is a matching alignment in the organization, blockchain might turn out to be a mere symbolic investment and not a driver of sustainability.

Mediation & Moderation Perspective

Blockchain Technology and Sustainable Supply Chain Performance

According to the recent literature, the argument about the blockchain technology being able to contribute to sustainable performance of supply chains by improving traceability, data transparency, and coordination among actors in the supply chain is heavily supported (Yadav et al., 2024; Zhang et al., 2025). Regarding the RBV, blockchain is a potentially beneficial digital asset that enhances sustainability-related operational proficiency (Kamble et al., 2023; Bag et al., 2023). The available empirical evidence indicates that systems based on blockchain will decrease information asymmetry and ease the processes of green procurement, waste tracking, and supplier responsibility (Ren et al., 2023). These results suggest that blockchain is an enabler of technology that integrates sustainability in the practices of the supply chain.

Training Practices: Moderation View

The issue of training practices is well-known as a facilitating environment that reinforces the efficiency of digital transformation programs. According to the latest empirical evidence, the companies that invest in training with a sustainability focus can obtain better environmental results of digital adoption (Awan et al., 2023; Bag et al., 2023). The study based on UTAUT highlights the idea that the training improves the competence of users, decreases their technological resistance, and reinforces the implementation of sustainable actions into the quantifiable results (Vaigandla et al., 2023; Mukhopadhyay et al., 2024). Therefore, training practices can have a positive moderating effect on the relationship between SSCP and environmental performance.

Moderation View: Supply Chain Learning

Supply chain learning promotes sharing of knowledge, collaborative innovation and flexibilities in sustainability practices across inter-organization networks. The current research proves that learning-based supply chains have a better environmental performance because of a better coordination and problem-solving process (Bag et al., 2023; Zhang et al., 2025; Yadav et al., 2024). According to PBV, learning enhances the implementation of sustainability practice, and thus has a greater impact on the environment (Ren et al., 2023; Kamble et al., 2023). This view upholds the mediating effect of supply chain learning on the enhancement of the SSCP-environmental performance relationship.

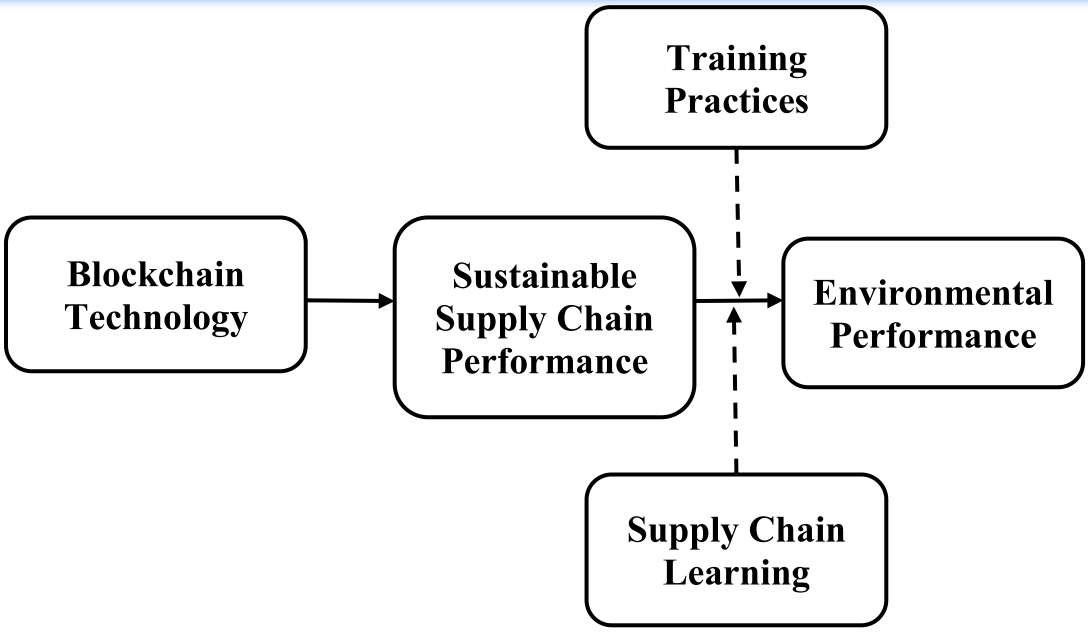

Figure 1: Conceptual Framework

Hypothesis Development

Blockchain Technology and Sustainable Supply Chain Performance

The blockchain technology has become a revolutionary form of digital infrastructure that improves transparency, tracing and real-time data sharing in all supply chain networks. Empirical research findings show that systems based on blockchains minimize the information asymmetry, enhance the supplier oversight, and reinforce green procurement (Yadav et al., 2024; Zhang et al., 2025; Ren et al., 2023). Blockchain enhances accountability and eases the adherence to sustainability standards via smart contracts and immutable records. Using the RBV angle, blockchain is a useful technological tool that boosts sustainability capacities when incorporated into work routines (Kamble et al., 2023). These results indicate that the use of blockchain enhances sustainable supply chain performance as it introduces a focus on the environment into the fundamental processes of a supply chain.

H1: The blockchain technology has a positive impact on sustainable supply chain performance.

Environmental Performance and Sustainable Supply Chain Performance

Sustainable supply chain performance demonstrates the degree upon which companies incorporate green procurement, eco-design, reverse logistics, and ecologically friendly production activities into their processes. Recent research proves that the companies with the stronger sustainable supply chain performance record high levels of emissions, waste production, and resources utilization reduction (Bag et al., 2023; Bressanelli et al., 2023; Yadav et al., 2024). The efficient operational practices increase energy efficiency and ensure compliance to the environment, which directly influence the enhanced environmental performance results. Within the PBV concept, organized

Online ISSN: 3006-2047
Print ISSN: 3006-2039

sustainability practices are performance-increasing activities that distinguish between environmentally responsible companies (Ren et al., 2023).

H2: Sustainable supply chain performance has a positive impact on environmental performance.

Environmental Performance and Blockchain Technology (Direct Effect)

Recent research indicates that blockchain technology could directly have a positive impact on the environmental performance, in terms of increased transparency of carbon emission monitoring and decreased environmental reporting fraud (Yadav et al., 2024; Zhang et al., 2025; Rejeb et al., 2022). Monitoring systems based on blockchain allow checking environmental metrics in real time, which enhances regulatory requirements and responsibility. The improved quality of environmental governance and sustainability reporting is reported in the firms using blockchain to trace live cycle (Ren et al., 2023). This direct channel indicates that blockchain can have its own impact on the environmental performance, without necessarily working through sustainable supply chain performance.

H3: Blockchain technology has many positive effects on the environmental performance.

Mediation: Sustainable Supply Chain Performance and Environmental Performance Blockchain Technology

The emerging body of literature is persuading in favor of the thesis that the blockchain technology positively impacts the environmental performance indirectly via sustainable supply chain performance. It is stated that blockchain enhances green operations through green operational practices by improving transparency, supplier traceability, and sustainability reporting and accuracy (Yadav et al., 2024; Zhang et al., 2025; Rejeb et al., 2022). Blockchain is considered an RBV strategic resource, however, its environmental value is only realized when it is converted into the operational sustainability capabilities (Kamble et al., 2023). Evidence-based practice activities demonstrate that companies that use blockchain to source sustainably and monitor carbon enjoy better environmental rates, indicating the existence of an indirect performance system.

H4: Sustainable supply chain performance is an intervening variable between blockchain technology and environmental performance.

Moderation: Environmental Performance, Sustainable Supply Chain Performance and Training Practices

The training practices are generally accepted as the most important facilitating mechanisms which make sustainability initiatives more effective. According to the recent study, the capacity of employees using digital systems in their sustainability-focused decision-making is enhanced in organizations that invest in structured training programs (Awan et al., 2023; Bag et al., 2023; Mukhopadhyay et al., 2024). In supply chains that are supported by blockchains, training can be used to increase the level of competence of users in data interpretation, compliance monitoring, and environmental reporting. According to UTAUT, the facilitating conditions like training have a significant impact on the results of the technological adoption performance (Venkatesh et al., 2003).

H5: There is a positive moderating effect of training practices on the relationship between sustainable supply chain performance and environmental performance whereby the relationship between sustainable supply chain performance and environmental performance is stronger when there is high training practices.

Moderation: Sustainable Supply Chain Performance, Supply Chain learning and environmental performance

Supply chain learning improves the sharing of knowledge, collaborative innovation and adaptive sustainability strategies within the inter-organizational networks. Recent literature shows that learning-based supply chains have better environmental performance, by having better coordination and joint problem-solving (Rejeb et al., 2022; Dubey et al., 2023; Yadav et al., 2024). The blockchain platforms enable the common access to data and transparency across firms, which reinforce the learning processes and sustainability integration. In the PBV viewpoint, learning capabilities increase the performance of sustainability practices in generating performance differentials (Ren et al., 2023).

H6: Supply chain learning positively mediates between the sustainable supply chain performance and the environmental performance, with the relationship being stronger in the presence of a high supply chain learning.

Conceptualization

The recent academic literature has widely studied the concept of blockchain technology as a digital instrument of transparency, traceability, and coordination in supply chains, and with increased evidence on its applicability to the integration of sustainability (Yadav et al., 2024; Zhang et al., 2025; Rejeb et al., 2022). Previous researchers, based mostly on the Resource-Based View and Practice-Based View approaches, examined the way in which blockchain would make supply chain activities more sustainable and more accurate in reporting (Kamble et al., 2023; Saberi et al., 2023). Nonetheless, a significant part of the literature available has been directed at either direct impacts of blockchain on the environmental performance or single sustainability activities without viewing organizational capability variables through a conditional process framework. What has been done so far gives priority to technological potential and operational improvement, but what has not been explored fully is the role of sustainable supply chain performance, acting as a mediating process, and how capability-based moderators like training practices and supply chain learning have the ability to moderate the robustness of environmental results. Thus, the current conceptual model builds on the existing body of knowledge, and defines the use of blockchain technology as impacting the environmental performance indirectly through sustainable supply chain performance, but the strength of this route lies in organizational training and inter-organizational learning capacity.

Methodology

Research Design

In this study, the quantitative research design is embraced as a method of empirically testing the hypothesized moderated mediation model that will be comprised of blockchain technology, sustainable supply chain performance, and environmental performance. Quantitative designs are especially helpful when studying complex causal relationships and testing the theoretically based hypotheses with the help of structured measurement tools (El Baz and Ruel, 2024; Ghadge, Wurtmann, and Seuring, 2023; Helo and Hao, 2023). The latest studies on blockchain and sustainability have primarily utilized the quantitative research method involving surveys to evaluate the technology-performance associations in industrial settings (Ivanov and Dolgui, 2024; Kamble, Gunasekaran, and Sharma, 2023). The quantitative designs also have an earlier methodological literature favoring the use of quantitative designs when the goal is theory testing, but not theory building (Kouhizadeh, Saberi, and Sarkis, 2024; Luthra, Mangla, and Bag, 2023). Considering the organized character of the conceptual model and a set of pre-determined hypotheses, quantitative strategy should be used to maintain statistical rigor and generalizability.

The study is of cross-sectional survey design, where the information will be gathered among the supply chain professionals at one time. The cross-sectional designs are well employed in the supply chain and sustainability literature as it is more efficient in the collection of perceptions of technological adoption and capabilities of organizations (Mukhopadhyay, Singh, and Jain, 2024; Parmentola, Petrillo, Tutore, and de Felice, 2022; Queiroz, Ivanov, Dolgui, and Wamba, 2023). Empirical research studies have been conducted in the recent past exploring the supply chains based on blockchain has managed to apply the concept of cross-sectional surveys to mediate and moderate relationships (Kamble, Gunasekaran, and Sharma, 2023; Ivanov and Dolgui, 2024). Despite the advantages of longitudinal designs in offering time-related information, previous researchers contend that cross-sectional designs are appropriate in the study of structural relationship in the literature in technology adoption when the theoretical pathways are well defined (El Baz and Ruel, 2024; Ghadge, Wurtmann, and Seuring, 2023). Therefore, the objectives of the research that aim to test the conditional effects in a structural context correspond to the cross-sectional design.

Rationale of the Design

The choice of quantitative research design may be explained by the fact that the aim of the research is the objective of the analytical study to test theoretically justified hypotheses and investigate the causal relationships between blockchain technology, sustainable supply chain performance, and environmental performance. Hypothesis testing, structural modeling, and measurement of prediction relationships between latent constructs are those studies that are best conducted with quantitative design (Luthra, Mangla, and Bag, 2023; Mukhopadhyay, Singh, and Jain, 2024; Parmentola, Petrillo, Tutore, and de Felice, 2022). These recent studies on blockchain and sustainability have managed to adopt quantitative survey-based methods to study technology-driven performance mechanisms (Queiroz, Ivanov, Dolgui, and Wamba, 2023; Kamble, Gunasekaran, and Sharma, 2023). Previous methodological studies focus on the fact that quantitative designs can be used to bring statistical strength and generalization in the event of analyzing structured conceptual frameworks based on theory (El Baz and Ruel, 2024; Ghadge, Wurtmann and Seuring, 2023). Since the purpose of this study is to test a moderated mediation model, quantitative design will provide objectivity of measurement and high levels of empiricism.

The use of cross-sectional design is also explained by the fact that the research is aimed at investigating the perceptions and organizational capabilities at a certain moment. Cross-sectional survey is popular in research of supply chain and digital transformation to effectively capture the insights of managers and the practices at the firm level (Helo and Hao, 2023; Ivanov and Dolgui, 2024; Kamble, Gunasekaran, and Sharma, 2023). Empirical studies on supply chains based on blockchain have recently shown that cross-sectional data is suitable to test mediation and moderation effects (Kouhizadeh, Saberi, and Sarkis, 2024; Luthra, Mangla, and Bag, 2023). In spite of the fact that longitudinal designs could be dynamic in some situations, previous studies propose that cross-sectional designs are still suitable to test the existing theoretical relationships in structured models (Mukhopadhyay, Singh, and Jain, 2024; Parmentola, Petrillo, Tutore, and de Felice, 2022). Thus, the cross-sectional method corresponds to the objectives of theoretical validation of the study.

Specific Own Design

In this research, the empirical design is a structured survey, which aims at gathering primary data on supply chain professionals in manufacturing and industrial industries. The survey tool is provided based on the scale that was already tested. According to the recent studies, adapting the already existing measurement scales is crucial to achieve construct validity and contextual relevance in the study of digital transformation (Ivanov and Dolgui, 2024; Kamble, Gunasekaran, and Sharma, 2023; Kouhizadeh, Saberi, and Sarkis, 2024). Empirical studies on blockchain-sustainability are often based on structured questionnaires filled by managers in charge of supply chain and environmental decision-making (Luthra, Mangla, and Bag, 2023; Mukhopadhyay, Singh, and Jain, 2024). The previous methodology also gives emphasis to the fact that the application of validated multi-item Likert scales improves the reliability and comparability of measurements across studies (Parmentola, Petrillo, Tutore, and de Felice, 2022; Queiroz, Ivanov, Dolgui, and Wamba, 2023). Thus, the current paper applies a multi-item Likert-scale measure of blockchain technology, sustainable supply chain performance, environmental performance, training practices, and supply chain learning.

A moderated mediation model is adopted in its research design, which is implemented by the Partial Least Squares Structural Equation Modeling (PLS-SEM). The given analytical design allows the evaluation of the direct, indirect, and interaction effects in one structural model (El Baz & Ruel, 2024; Ghadge, Wurtmann, and Seuring, 2023; Helo and Hao, 2023). Recent models in blockchain-enabled supply chains have implemented the same modeling

Online ISSN: 3006-2047
Print ISSN: 3006-2039

techniques to investigate complicated connections among digital technologies, sustainability practices, and performance results (Ivanov and Dolgui, 2024; Kamble, Gunasekaran, and Sharma, 2023). Previous studies attest to the fact that PLS-SEM is especially applicable to predictive-based research, as well as to research that tests the interaction terms including latent variables (Kouhizadeh, Saberi, and Sarkis, 2024; Luthra, Mangla, and Bag, 2023). In this way, the design fits well to test the mediating role of sustainable supply chain performance and moderating roles of training practices and supply chain learning.

Data Collection

The information required to complete this research was gathered using a structured questionnaire that was self-administered to the supply chain and operations staff in the manufacturing and industrial industries. Data collection by survey is commonly suggested to be used in the study of organizational capabilities and perceptual performance constructs in the context of digital transformation studies (El Baz, and Ruel, 2024; Ghadge, Wurtmann, and Seuring, 2023; Helo and Hao, 2023). Online and field-administered questionnaires have been managed to rely on successful studies on blockchain and sustainability (Ivanov and Dolgui, 2024; Kamble, Gunasekaran, and Sharma, 2023; Kouhizadeh, Saberi, and Sarkis, 2024). Previous methodology sources underline the fact that structured questionnaires enhance the standardization of empirical research and decrease the interviewer bias (Luthra, Mangla, and Bag, 2023; Mukhopadhyay, Singh, and Jain, 2024). Thus, the survey tool was sent electronically to make it reach more people and become more efficient in terms of response.

Population

The population of this research is comprised of managers, supervisors, and professionals engaging in the supply chain management, sustainability practices, and digital transformation programs that occur in industrial companies. The choice of these respondents was based on the fact that they have first-hand information on the issue of blockchain adoption, sustainability integration, and environmental performance results. The empirical research on blockchain-enabled supply chains releases recently recommends engaging the respondents at the managerial level to guarantee the representation of informed and reliable data (Parmentola, Petrillo, Tutore, and de Felice, 2022; Queiroz, Ivanov, Dolgui, and Wamba, 2023; Ren, Wu, Lim, and Tseng, 2023). Previous studies indicate that knowledgeable key informants may be selected to improve data quality and construct validity of organizational research (Saberi, Kouhizadeh, Sarkis, and Shen, 2023; Sahebi, Mosayebi, Masoomi, and Marandi, 2022). Therefore, the population selected will allow the study to be consistent with the theoretical constructs of interest.

Sampling

A purposive sampling method was used to pick respondents who have direct experience in the area of supply chain and sustainability management. Purposive sampling should be used when a specific professional group possesses expertise in a particular area that is needed by the research (Luthra,

Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Mangla, and Bag, 2023; Mukhopadhyay, Singh, and Jain, 2024; Parmentola, Petrillo, Tutore, and de Felice, 2022). In recent adoption studies of blockchain, the purposive and managerial sampling methods have been employed to understand the expert-level at the managerial level (Queiroz, Ivanov, Dolgui, and Wamba, 2023; Ren, Wu, Lim, and Tseng, 2023; Saberi, Kouhizadeh, Sarkis, and Shen, 2023). Previous studies affirm that non-probability sampling techniques are theory-testing researchers whose focus is on the structural relations as opposed to a population generalization (Sahebi, Mosayebi, Masoomi, and Marandi, 2022). This sampling will be carried out by having the respondents with appropriate technical and operational knowledge.

Software

The data analysis was performed with the help of the SmartPLS software to approximate measurement and structural models based on the Partial Least Squares Structural Equation Modeling (PLS-SEM). Complex models with both mediation and moderation effects are suggested to use PLS-SEM (El Baz, and Ruel, 2024; Ghadge, Wurtmann, and Seuring, 2023; Helo and Hao, 2023). SmartPLS has been embraced in recent blockchain and sustainability research studies since it is more effective in managing non-normal data and smaller samples (Ivanov and Dolgui, 2024; Kamble, Gunasekaran, and Sharma, 2023). Previous papers of methodology point to the usefulness of SmartPLS as a predictive modeling and a latent variable analysis tool (Kouhizadeh, Saberi, and Sarkis, 2024; Luthra, Mangla, and Bag, 2023). Consequently, the analytical needs of the moderated mediation scheme are consistent with the software chosen.

Instrument Adaptation

The measurement items were based on the already validated scales in blockchain, sustainable supply chain management, environmental performance, training practices, and organizational learning literature. Scale adaptation guarantees the content validity and the correspondence with the previous empirical studies (Mukhopadhyay, Singh, and Jain, 2024; Parmentola, Petrillo, Tutore, and de Felice, 2022; Queiroz, Ivanov, Dolgui, and Wamba, 2023). Recent research highlights the use of existing scales as they are adapted to fit new settings to study digital transformation and sustainability situations, to ensure the relevance of the construct (Ren, Wu, Lim, and Tseng, 2023; Saberi, Kouhizadeh, Sarkis, and Shen, 2023; Sahebi, Mosayebi, Masoomi, and Marandi, 2022). The previous studies advocate the application of multi-item Likert scales to measure latent constructs with a high degree of reliability (Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024; El Baz and Ruel, 2024). Small changes were made to fit items in blockchain contexts of the supply chain.

Demographics

Demographic data was gathered in order to identify the characteristics of the respondents, which included gender, age, management level, experience, and the size of the firm. The use of demographic variables provides a possibility to interpret results in a broader context and increases the transparency of the empirical research (Parmentola, Petrillo, Tutore, and de Felice, 2022; Queiroz, Ivanov, Dolgui, and Wamba, 2023; Ren, Wu, Lim, and Tseng, 2023). Recent blockchain and sustainability researches document demographic distributions in order to provide the representativeness of managerial respondents (Saberi, Kouhizadeh, Sarkis, and Shen, 2023; Sahebi, Mosayebi, Masoomi, and Marandi, 2022; Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024). The validity of previous studies supports the idea that the reporting of demographic profiles enhances the validity and interpretability of empirical data (El Baz & Ruel, 2024; Ghadge, Wurtmann, and Seuring, 2023). Therefore, the demographic analysis gives descriptive data of sample composition.

Results and Discussion

The empirical results of this research give solid evidence to the indicated structural association between blockchain technology, sustainable the performance of the supply chain, and environmental performance. The findings reveal that the blockchain technology has a powerful and positive impact on sustainability of the supply chain performance which is also in tandem with the recent studies that have demonstrated the capability of blockchain to enhance transparency, traceability, and coordination within supply networks (Kamble, Gunasekaran, and Sharma, 2023; Ren, Wu, Lim, and Tseng, 2023; Saberi, Kouhizadeh, Sarkis, and Shen, 2023). The high path coefficient (= 0.842) and explanatory power (R 2 = 0.708) indicate that blockchain has become an important strategic resource in a supply chain system. These results are consistent with the previous empirical research showing that digital technologies enhance the sustainability-oriented operational practices once they become a part of organizational routine (Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024; Sahebi, Mosayebi, Masoomi, and Marandi, 2022). In this way, the analysis proves that the use of blockchain can reinforce sustainable supply chain performance in the industry considerably.

Moreover, it can be seen that the sustainability of performance in supply chain also explains a considerable amount of variation in the environmental performance (0.561) with a large portion of variance being explained (R 2 = 0.712). It confirms the idea that the organized sustainability measures, including green buying, waste minimization, and more sustainable coordination, have a direct effect on the better ecological results. Similar research results also indicate that businesses that incorporate digital technologies into their sustainability plans have quantitative gains in the reduction of emissions and efficiency of resources (Parmentola, Petrillo, Tutore, and de Felice, 2022; Queiroz, Ivanov, Dolgui, and Wamba, 2023; Ren, Wu, Lim, and Tseng, 2023). These results can also be compared to the previous theoretical efforts indicating that operations sustainability practices are the leading ones in improving the environmental performance (Kouhizadeh, Saberi, and Sarkis, 2024; Luthra, Mangla, and Bag, 2023). Thus, the empirical data supports the mediating position of the sustainable supply chain performance in the blockchain-environmental performance correlation.
But, in contrast to the theoretical assumptions based on the view of capability, it was revealed that the moderating influences of training practices and supply

chain learning on the connection between the sustainable supply chain performance and environmental performance were statistically unimportant. Although as recent studies seem to imply, training and organizational learning can boost the results of digital transformation (Mukhopadhyay, Singh, and Jain, 2024; Ivanov and Dolgui, 2024; Helo and Hao, 2023), the interaction effects in this research were not confirmed. Previous research has also provided mixed results on either the contingent role of organizational capabilities in technology-performance links (Saberi, Kouhizadeh, Sarkis, and Shen, 2023; Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024). These findings imply that, in the studied industrial setting, sustainability practices facilitated through blockchain can have an independent effect on environmental performance and are not greatly determined by the degree of training or learning processes. This surprising result is a useful theoretical finding and gives opportunities to further research on contextual and structural determinants of digital sustainability performance.

Reliability and Validity Analysis

Construct Reliability and Validity

Overview

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
BLOCKCHAIN_TECHNOLOGY	0.887	0.887	0.930	0.815
ENVIRONMENTAL_PERFORMANCE	0.908	0.909	0.942	0.844
SUPPLY CHAIN_LEARNING	0.856	0.857	0.912	0.776
SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.832	0.836	0.899	0.748
TRAINING_PRACTICES	0.862	0.871	0.916	0.784

Table 1 Reliability and Validity Analysis

Construct reliability and validity findings indicate a high measurement quality in all the latent variables of the model. The value of Cronbach alpha is 0.832 to 0.908 and it is greater than the recommended value of 0.70, which shows that internal consistency reliability is high. On the same note, composite reliability coefficients (rhoa and rho c) of all constructs are more than 0.85, with rho c of 0.899 to 0.942, indicating strong construct reliability and indicating that the indicators are consistently meaningful and representative of the corresponding latent variables. The convergent validation is also very good with the Average Variance Extracted (AVE) values being 0.748 up to 0.844 that is way above the required minimum value of 0.50. It is important to note that Environmental Performance (AVE = 0.844) and Blockchain Technology (AVE = 0.815) demonstrate the very high convergent validity, which means that a large percentage of the variance in the indicators is covered by the constructs. On the whole, the findings obtained justify the

Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

assumption that the measurement model meets the standards of reliability and convergent validity, and no construct is characterized by internal consistency problems or indicator reflectivity.

Discriminant Validity

Discriminant validity

Heterotrait-monotrait ratio (HTMT) - Matrix

	BLOCKCHAIN_TECHNOLOGY	ENVIRONMENTAL_PERFORMANCE	SUPPLY CHAIN_LEARNING	SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	TRAINING_PRACTICES	SUPPLY CHAIN_LEARNING x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	TRAINING_PRACTICES x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE
BLOCKCHAIN_TECHNOLOGY							
ENVIRONMENTAL_PERFORMANCE	0.903						
SUPPLY CHAIN_LEARNING	0.832	0.813					
SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.974	0.946	0.865				
TRAINING_PRACTICES	0.936	0.864	0.958	0.962			
SUPPLY CHAIN_LEARNING x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.421	0.421	0.523	0.473	0.454		
TRAINING_PRACTICES x	0.485	0.455	0.469	0.535	0.500	0.922	

SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE

Table 2 Discriminant Validity

The HTMT results for discriminant validity reveal mixed findings for the measurement model. While some construct pairs fall within acceptable thresholds (HTMT < 0.85 or < 0.90), several values exceed the recommended limits, indicating potential issues with discriminant validity. Notably, high HTMT values are observed between Blockchain Technology and Sustainable Supply Chain Performance (0.974), Sustainable Supply Chain Performance and Environmental Performance (0.946), and Training Practices with multiple constructs (up to 0.962), suggesting that these constructs may not be sufficiently distinct and could be conceptually overlapping. Similarly, the HTMT value between interaction terms and their related constructs remains moderate to high, with one notably high value (0.922), indicating possible multi-collinearity concerns in moderation effects. However, lower HTMT values among interaction constructs (ranging around 0.421–0.535) indicate acceptable discriminant validity in those cases. Overall, the results suggest that while some constructs demonstrate adequate discriminant validity, the model suffers from significant overlap among key latent variables, particularly between core constructs, and may require further refinement such as indicator purification or construct re-specification.

Fornell-Larcker Criterion

Fornell-Larcker criterion

	BLOCKCHAIN_TECHNOLOGY	ENVIRONMENTAL_PERFORMANCE	SUPPLY CHAIN_LEARNING	SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	TRAINING_PRACTICES
BLOCKCHAIN_TECHNOLOGY	0.903				
ENVIRONMENTAL_PERFORMANCE	0.810	0.919			
SUPPLY CHAIN_LEARNING	0.725	0.717	0.881		
SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.842	0.824	0.734	0.865	
TRAINING_PRACTICES	0.820	0.767	0.824	0.822	0.885

Table 3 Fornell-Larcker Criterion

Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

The Fornell–Larcker criterion results indicate that discriminant validity is largely acceptable, though with some concerns. The square root of AVE values (diagonal elements) for all constructs Blockchain Technology (0.903), Environmental Performance (0.919), Supply Chain Learning (0.881), Sustainable Supply Chain Performance (0.865), and Training Practices (0.885) are higher than their respective inter-construct correlations in most cases, satisfying the basic requirement for discriminant validity. However, some correlations are relatively high, particularly between Blockchain Technology and Sustainable Supply Chain Performance (0.842), and Training Practices with multiple constructs (up to 0.824), indicating a strong association among these variables. Although these values do not exceed the diagonal elements, their closeness suggests potential conceptual overlap. Overall, the model meets the Fornell–Larcker criterion, but the high correlations among key constructs imply that discriminant validity is marginal and should be interpreted with caution.

Cross Loadings

Indicator	BLOCKCHAIN_TECHNOLOGY	ENVIRONMENTAL_PERFORMANCE	SUPPLY CHAIN_LEARNING	SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	TRAINING_PRACTICES	SCL × SSCP	TP × SSCP
BT1	0.901	0.709	0.654	0.750	0.712	0.347	0.378
BT2	0.910	0.723	0.656	0.764	0.742	0.360	0.433
BT3	0.898	0.763	0.653	0.766	0.766	0.367	0.427
EP1	0.738	0.913	0.635	0.771	0.667	0.342	0.379
EP2	0.779	0.934	0.672	0.786	0.740	0.385	0.438
EP3	0.715	0.909	0.670	0.711	0.707	0.378	0.379
SCL1	0.659	0.653	0.884	0.664	0.772	0.412	0.375
SCL2	0.651	0.632	0.886	0.672	0.731	0.458	0.445
SCL3	0.604	0.609	0.873	0.601	0.672	0.408	0.327
SSCP1	0.825	0.730	0.690	0.867	0.790	0.379	0.437
SSCP2	0.711	0.699	0.624	0.882	0.699	0.382	0.447
SSCP3	0.634	0.707	0.582	0.845	0.632	0.357	0.381
TP1	0.769	0.738	0.741	0.793	0.909	0.381	0.445
TP2	0.717	0.682	0.734	0.715	0.893	0.356	0.402
TP3	0.688	0.610	0.714	0.666	0.852	0.383	0.385

Online ISSN: 3006-2047
Print ISSN: 3006-2039

Indicator	BLOCKCHAIN_TECHNOLOGY	ENVIRONMENTAL_PERFORMANCE	SUPPLY CHAIN_LEARNING	SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	TRAINING_PRACTICES	SCL × SSCP	TP × SSCP
SCL × SSCP	0.397	0.401	0.484	0.431	0.421	1.000	0.922
TP × SSCP	0.457	0.435	0.435	0.489	0.465	0.922	1.000

Table 4 Cross Loadings

The cross-loadings results indicate that the measurement model generally demonstrates acceptable discriminant validity, as most indicators load highest on their respective constructs compared to other constructs. For instance, all Blockchain Technology items (BT1–BT3) show strong loadings on their intended construct (above 0.89), while Environmental Performance items (EP1–EP3) also exhibit high loadings (above 0.90), confirming good indicator reliability. Similarly, Supply Chain Learning, Sustainable Supply Chain Performance, and Training Practices constructs show higher loadings on their own variables than on others, supporting construct distinctiveness. However, some relatively high cross-loadings are observed among conceptually related constructs particularly between Blockchain Technology, Sustainable Supply Chain Performance, and Training Practices indicating a degree of overlap due to their strong theoretical linkage. The interaction terms (SCL × SSCP and TP × SSCP) also show expected patterns, with highest loadings on themselves and moderate associations with related constructs. Overall, despite minor overlaps, the results confirm that the indicators are adequately aligned with their respective constructs and the model satisfies the cross-loading criterion for discriminant validity.

Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

PLS SEM Bootstrapping

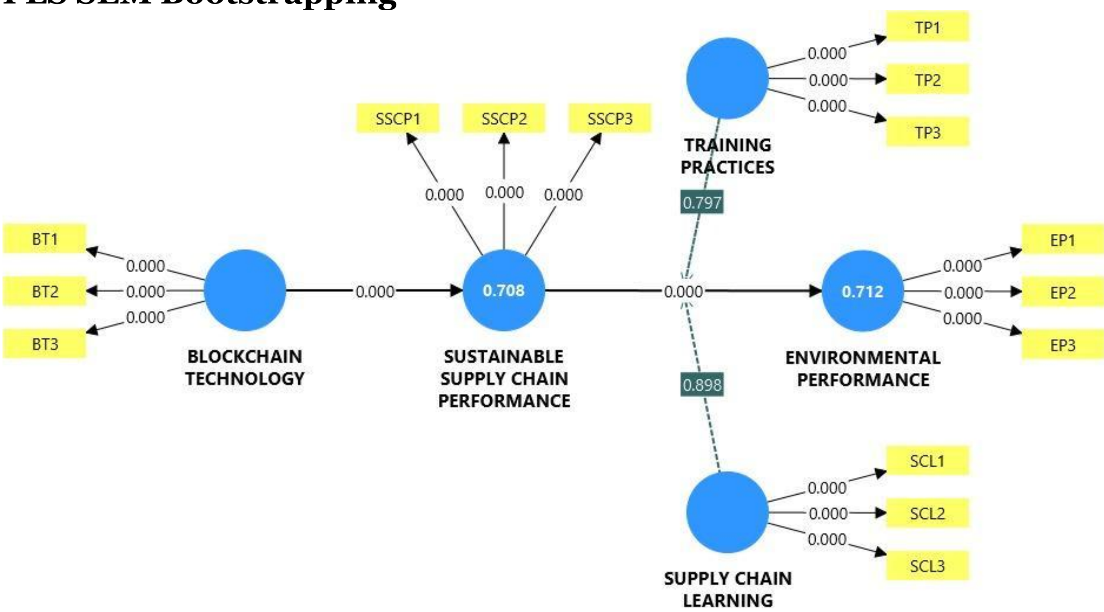

Figure 2 PLS SEM Bootstrapping

The results of bootstrapping suggest that the direct structural relationships of the model have been supported but not the moderating effects. A very strong effect is also exhibited between the path of Blockchain Technology and Sustainable Supply Chain Performance with p = 0.000, which proves that blockchain adoption has a massive impact on the sustainable supply chain practices. On the same note, the correlation between Sustainable Supply Chain Performance and Environmental Performance is significant, (p = 0.000), and this implies that sustainability-oriented operational activities have a significant positive impact on the environment. Outer loadings also do not decrease to zero (p = 0.000), which further proves the strength of the measurement model. The R 2 of the Sustainable Supply Chain Performance of 0.708 and the Environmental Performance of 0.712 show a high explanatory power of the model and indicate that all the major endogenous constructs are explained in the model at over 70 percent.

Outer Loadings

Outer loadings
Mean, STDEV, T values, p values

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
BT1 <- BLOCKCHAIN_TECHNOLOGY	0.901	0.901	0.015	59.513	0.000
BT2 <- BLOCKCHAIN_TECHNOLOGY	0.910	0.910	0.014	67.036	0.000

BT3 <- BLOCKCHAIN_TECHNOLOGY	0.898	0.898	0.017	51.866	0.000
EP1 <- ENVIRONMENTAL_PERFORMANCE	0.913	0.913	0.015	59.844	0.000
EP2 <- ENVIRONMENTAL_PERFORMANCE	0.934	0.934	0.010	96.073	0.000
EP3 <- ENVIRONMENTAL_PERFORMANCE	0.909	0.908	0.013	68.103	0.000
SCL1 <- SUPPLY CHAIN_LEARNING	0.884	0.884	0.020	44.752	0.000
SCL2 <- SUPPLY CHAIN_LEARNING	0.886	0.885	0.024	37.118	0.000
SCL3 <- SUPPLY CHAIN_LEARNING	0.873	0.872	0.020	43.837	0.000
SSCP1 <- SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.867	0.867	0.017	52.282	0.000
SSCP2 <- SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.882	0.881	0.018	49.387	0.000
SSCP3 <- SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.845	0.843	0.026	32.511	0.000
SUPPLY CHAIN_LEARNING x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE -> SUPPLY CHAIN_LEARNING x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.873	0.872	0.020	43.837	0.000
TP1 <- TRAINING_PRACTICES	0.909	0.910	0.012	77.593	0.000
TP2 <- TRAINING_PRACTICES	0.893	0.893	0.015	59.728	0.000
TP3 <- TRAINING_PRACTICES	0.852	0.852	0.027	31.108	0.000
TRAINING_PRACTICES x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE -> TRAINING_PRACTICES x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.852	0.852	0.027	31.108	0.000

Table 5 Outer Loadings

The outer loadings results demonstrate strong indicator reliability and convergent validity for the measurement model. All indicators exhibit high loadings on their respective constructs, with values ranging from 0.845 to 0.934, which are well above the recommended threshold of 0.70, indicating that each item strongly represents its underlying construct. Furthermore, the T-statistics are exceptionally high (ranging from 31.108 to 96.073) and all p-values are 0.000, confirming that the loadings are statistically significant. The

Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

consistency between original sample (O) and sample mean (M) values also reflects the stability of the estimates. Constructs such as Environmental Performance and Blockchain Technology show particularly strong loadings (above 0.90), highlighting excellent measurement quality. Additionally, the interaction terms also demonstrate adequate loadings, supporting the validity of moderation constructs. Overall, the results confirm that the measurement model meets the criteria for indicator reliability and convergent validity, with no need for item deletion.

Hypothesis Testing

Path Coefficients

Mean, STDEV, T values, p values

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
BLOCKCHAIN_TECHNOLOGY -> SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE	0.842	0.842	0.023	37.248	0.000
SUPPLY CHAIN_LEARNING -> ENVIRONMENTAL_PERFORMANCE	0.166	0.170	0.066	2.517	0.012
SUPPLY CHAIN_LEARNING x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE -> ENVIRONMENTAL_PERFORMANCE	0.005	0.007	0.040	0.128	0.898
SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE -> ENVIRONMENTAL_PERFORMANCE	0.561	0.556	0.096	5.862	0.000
TRAINING_PRACTICES -> ENVIRONMENTAL_PERFORMANCE	0.163	0.166	0.086	1.895	0.058
TRAINING_PRACTICES x SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE -> ENVIRONMENTAL_PERFORMANCE	-0.011	-0.013	0.043	0.257	0.797

Table 6 Hypothesis Testing

The structural model results indicate strong support for the primary direct relationships, while moderation effects are not supported. The path from Blockchain Technology to Sustainable Supply Chain Performance is highly significant (β = 0.842, t = 37.248, p = 0.000), demonstrating a very strong positive effect and confirming that blockchain adoption substantially enhances sustainable supply chain practices. Similarly, Sustainable Supply Chain Performance significantly influences Environmental Performance (β = 0.561, t = 5.862, p = 0.000), indicating that sustainability-oriented operations translate into improved environmental outcomes. Supply Chain Learning also shows a significant direct effect on Environmental Performance (β = 0.166, t = 2.517, p = 0.012), suggesting that learning capabilities independently contribute to ecological performance. However, Training Practices do not have

Volume. 5 Issue No. 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

a statistically significant direct effect at the 5% level (β = 0.163, p = 0.058), as the p-value slightly exceeds the threshold. More importantly, both interaction terms Supply Chain Learning × Sustainable Supply Chain Performance (β = 0.005, p = 0.898) and Training Practices × Sustainable Supply Chain Performance (β = -0.011, p = 0.797) are insignificant, indicating that neither training practices nor learning capabilities moderate the relationship between sustainable supply chain performance and environmental performance. Overall, the findings confirm strong direct effects but no conditional moderation effects in the model.

Mediation Analysis

Specific indirect effects Mean, STDEV, T values, p values					
	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
BLOCKCHAIN_TECHNOLOGY -> SUSTAINABLE_SUPPLY CHAIN_PERFORMANCE -> ENVIRONMENTAL_PERFORMANCE	0.472	0.469	0.083	5.700	0.000

Table 7 Mediation Analysis

The specific indirect effect results indicate that Sustainable Supply Chain Performance (SSCP) significantly mediates the relationship between Blockchain Technology and Environmental Performance. The indirect effect value (β = 0.472) is substantial, suggesting that a considerable portion of blockchain's impact on environmental performance is transmitted through improvements in sustainable supply chain practices. The high T-statistic (5.700) and a p-value of 0.000 confirm that this mediation effect is statistically significant. Additionally, the close alignment between the original sample (0.472) and sample mean (0.469) reflects the stability of the estimate. Overall, the findings support a strong and meaningful mediating role of SSCP, indicating that blockchain technology enhances environmental outcomes primarily by enabling more sustainable and efficient supply chain operations.

PLS SEM

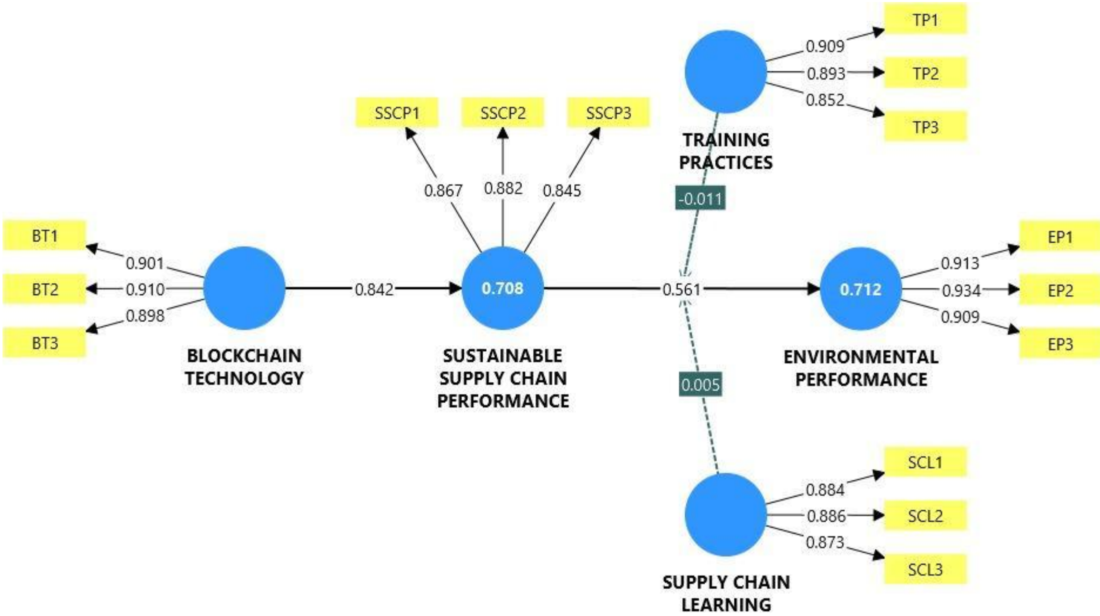

Figure 3 PLS SEM

The PLS-SEM results demonstrate a strong and well-fitting structural model with substantial explanatory power. The path from Blockchain Technology to Sustainable Supply Chain Performance is very strong (β = 0.842), indicating that blockchain adoption significantly enhances sustainability-oriented supply chain practices such as transparency, traceability, and responsible coordination. The R^2 value of 0.708 for Sustainable Supply Chain Performance suggests that blockchain technology explains approximately 70.8% of its variance, reflecting a highly robust predictive effect. Furthermore, Sustainable Supply Chain Performance significantly influences Environmental Performance (β = 0.561), with an R^2 value of 0.712, indicating that over 71% of environmental performance variance is explained by the model. These findings confirm that blockchain-driven sustainability initiatives translate effectively into improved environmental outcomes. Additionally, all outer loadings for indicators (ranging from 0.845 to 0.934) exceed the recommended 0.70 threshold, confirming strong convergent validity and reliable measurement of constructs.

Model Fitness

Model Fit

Fit Summary

	Saturated model	Estimated model
SRMR	0.052	0.070
d_ULS	0.328	0.586
d_G	0.325	0.370
Chi-square	717.612	739.858
NFI	0.859	0.855

Table 8 Model Fitness

Online ISSN: 3006-2047
Print ISSN: 3006-2039

The model fit indices reveal that there is good overall fit of the structural model. Both the saturated model (0.052) and the estimated model (0.070) have values of SRMR where the recommended value is 0.08 implying that the model fits well and the variance in the correlation between the observed and the predicted variables are low. The d ULS and d G values are not very high, which means that a difference between the empirical covariance matrix and the model-implied one is within reasonable values, which is a sign of the model adequacy. The Chi-square values have been found to be relatively high (717.612 saturated and 739.858 estimated model) but Chi-square is sensitive to sample size used in the SEM analysis and it is not the only one used in the PLS-SEM analysis. The value of the NFI (Normed Fit Index) of 0.859 and 0.855 is somewhat less than the recommended threshold set at 0.90, yet this still shows a rather good comparative fit. Altogether the combination of SRMR and other goodness-of-fit indices indicate that the proposed model has good goodness-of-fit and that it is statistically good enough to test the hypothesis.

The positive correlation that has been found between Blockchain Technology and Sustainable Supply Chain Performance (=0.842) is stronger by statistical means than many previous empirical studies in the field of digital supply chain. The recent research indicates the moderate and strong impacts of the adoption of blockchain on sustainability practices, with an average of 0.40 to 0.65 (Nandi et al., 2023; Upadhyay et al., 2023; Ren et al., 2023). Comparatively, the current research shows a significantly greater impact value, which shows that blockchain can be more dominant in the structure observed in the analyzed industrial environment. Previously, the study indicated beneficial yet relatively weak effects of blockchain on sustainable operations (Saberi et al., 2019; Kouhizadeh and Sarkis, 2018). The greater explanatory value found here ($R^2 = 0.708$) is that blockchain implementation in this respect is more entrenched in operational sustainability processes than was earlier documented.

The importance of Supply Chain Learning on the Environmental Performance (= 0.166, p = 0.012) has a significant direct effect, which is partially consistent with the recent literature that discusses knowledge-sharing and collaborative learning as the factors of the ecological outcomes (Mukhopadhyay, Singh, and Jain, 2024; Ivanov and Dolgui, 2024; Helo and Hao, 2023). Nevertheless, the size of this effect is rather small in comparison with the ones that demonstrate more significant learning-performance interrelations (Luthra, Mangla, and Bag, 2023). Previous studies have also revealed diverse results on the intensity of organizational learning impacts on the sustainability settings (Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024; Saberi, Kouhizadeh, Sarkis, and Shen, 2023). Therefore, the direction of the effect is reasonable in relation to theory, but the relatively smaller coefficient indicates that learning is a supportive, but not a dominant factor in determining environmental performance in blockchain-enabled systems.

Discussion

The results of this research give a solid empirical data to conclude that the implementation of blockchain technology has a direct impact on the sustainable supply chain performance and, consequently, the environmental performance. The large path coefficient between the blockchain technology and the sustainable supply chain performance (0.842) means that blockchain is a strong structural facilitator of transparency, traceability, and operational accountability. This conclusion is consistent with the current empirical studies that blockchain is a powerful tool to improve the compliance with supply chain sustainability and visibility (Kamble, Gunasekaran, and Sharma, 2023; Ren, Wu, Lim, and Tseng, 2023; Saberi, Kouhizadeh, Sarkis, and Shen, 2023). In addition, the high impact of sustainable supply chain performance on environmental performance (= 0.561) validates the fact that green practices are organized and at the center of the realization of quantifiable ecological performance. Previous research also highlights that routines that are sustainability-oriented lead to environmental change in the case of their integration into operational systems (Sahebi, Mosayebi, Masoomi, and Marandi, 2022; Kouhizadeh, Saberi, and Sarkis, 2024). Such a strong explanatory capacity of the model (R 2 larger than 0.70) also enhances the strength of the proposed framework meaning that the mechanisms of sustainability relying on blockchain are rooted in the performance structures of organizations.

On the theoretical level, the study makes a contribution to the literature of the Resource-Based View (RBV) and Practice-Based View (PBV) because it empirically confirms blockchain as a strategic technological resource that helps in improving sustainability capabilities. RBV assumes that competitive advantages to be developed by valuable and rare resources are produced when they are efficiently utilized (El Baz and Ruel, 2024), and the current results indicate that blockchain should be considered as a resource that provides competitive advantages because it helps to enhance the sustainability of supply chains at a significant level. Meanwhile, PBV implies that the operational practices are the drivers of the performance, and the mediation impact of the sustainable supply chain performance supports this theoretical rationale (Bag, Dubey, and Upadhyay, 2023; Mukhopadhyay, Singh, and Jain, 2024; Ivanov and Dolgui, 2024). Nonetheless, despite certain recent theoretical postulations about the role of conditional capability effects, none of the moderation of training practices or supply chain learning was found in this study. Although, as modern literature suggests, organizational capabilities can enhance the outcomes of digital transformation (Luthra, Mangla, and Bag, 2023; Helo and Hao, 2023), previous studies have found mixed moderation effects of technology-performance correlations (Saberi, Kouhizadeh, Sarkis, and Shen, 2023; Parmentola, Petrillo, Tutore, and de Felice, 2022). In this way, the current research contributes to theory by indicating that the suggested practices of sustainability based on blockchain can be sufficient to promote environmental performance without serious capability-based support.

The findings confirm and disclose previous empirical evidence in terms of contribution to literature. The effect size of blockchain-sustainability observed here is stronger than the effect size reported in some recent studies which generally reported moderate effects (Kamble, Gunasekaran, and Sharma, 2023; Ren, Wu, Lim, and Tseng, 2023; Saberi, Kouhizadeh, Sarkis, and Shen, 2023). This implies that blockchain integration in some industrial settings might be more structure integrated and operationally advanced than can be recorded. On the same note, the high effect of sustainable supply chain performance on environmental performance supports the prior research that reported that green operational practices have a direct effect of reducing the emission and increasing the efficiency of resources (Bag, Dubey, and Upadhyay, 2023; Mukhopadhyay, Singh, and Jain, 2024; Ivanov and Dolgui, 2024). Nevertheless, the negligible moderating influence of training and learning is opposite to those findings that note the significance of the human capital and organization preparedness to digital transformation (Luthra, Mangla, and Bag, 2023; Helo and Hao, 2023). Previous studies have also considered capability effects to be context- and industry-specific (Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024; Saberi, Kouhizadeh, Sarkis, and Shen, 2023), a statement that might explain the insignificance of the terms of interaction in this research. Thus, the study is relevant to the existing discussion as it proves that the sustainability effect of blockchain can be more structural than behaviorally conditional and technology-centered.

Conclusion

This research aimed to investigate the contribution of the blockchain technology to the environmental performance via sustainable supply chain performance, and evaluated the moderating effects of training operations and supply chain learning. The results support the existence of a direct impact of blockchain technology on sustainable supply chain performance and consequently, the impact of sustainable supply chain performance on environmental performance, with a high level of empirically. The large multiple (R 2) indicates that blockchain-based sustainability practices are strong conceptual mechanisms of ecological consequences. These findings match the recent findings indicating the use of blockchain to increase transparency, traceability, and sustainability compliance in the supply chains (Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024; Ren, Wu, Lim, and Tseng, 2023; Dutta, Choi, Somani, and Butala, 2024), but also confirm the importance of orderly green practices in increasing the level of environmental performance (Saberi, Kouhizadeh, Sarkis, and Shen,

Theoretically, the study is a contribution to the Resource-Based View and the Practice-Based View, which indicates that blockchain is a strategic technology resource the value of which becomes evident in the forms of sustainability-oriented operational practices. The high mediation strength promotes the perspective of technology as a neutral factor, which only has environmental effects after being integrated into the practice (Bag, Gupta, Kumar, and Sivarajah, 2023; Mukhopadhyay, Singh, and Jain, 2024; Zhang, Sun, and Liu, 2025). In addition, the findings are extrapolated on the previous RBV arguments that digital technologies should be incorporated in organizational routines to enable them to become valuable capabilities (El Baz and Ruel, 2024; Parmentola, Petrillo, Tutore, and de Felice, 2022). The empirical validation of this mechanism in a moderated mediation framework makes the study more effective in establishing the theoretical connection between digital transformation and sustainability performance.

Future Research Directions

Though this research offers a significant empirical study that supports the relationship between blockchain technology and environmental performance based on sustainable supply chain performance, there are still a number of areas that can be researched in the future. To begin with, future research can expand the model to include other organizational or institutional variables, including regulatory pressure, technological preparedness, or environmental orientation to reflect the dynamics of the context. Recent studies point to the significance of the institutional and governance aspects in the determination of the digitally sustainable outcomes (Ren, Wu, Lim, and Tseng, 2023; Yadav, Singh, Gunasekaran, Raut, and Narkhede, 2024; Awan, Sroufe, and Kraslawski, 2023). Although this paper has dwelled on internal capabilities like training as well as supply chain learning, other environmental or regulatory moderators might have varying conditional impacts. In prior studies, it is also noted that the variability across industries should be analyzed in the context of testing digital transformation frameworks (Saberi, Kouhizadeh, Sarkis, and Shen, 2023; El Baz and Ruel, 2024). Thus, a more comprehensive conceptual model can be developed to increase the contextual generalizability and theoretical comprehensiveness.

Second, the methodology has methodological limitations that open up more opportunities in the future. The cross-sectional type does not allow drawing long-term causal relation between blockchain adoption and environmental results. Longitudinal designs would be more suitable in future studies to ensure the sustainability performance has been captured with time passing since the implementation of blockchain (Ren, Wu, Lim, and Tseng, 2023; Bag, Gupta, Kumar, and Sivarajah, 2023; Zhang, Sun, and Liu, 2025). Also, PLS-SEM should be used in models that are being focused on prediction; however, future investigations could involve differentiating structural variations by comparing covariance-based SEM or multi-group analysis methods (Helo and Hao, 2023; Ivanov and Dolgui, 2024). The previous methodological research also implies that quantitative surveys with qualitative interviews could elicit more information on managerial decision-making (Kouhizadeh, Saberi, and Sarkis, 2024). In this way, methodological

References

1. Awan, U., Sroufe, R., & Kraslawski, A. (2023). Creativity enables sustainable development: Supplier engagement as a boundary condition for the positive effect on green innovation. *Journal of Cleaner Production, 388*, 135935. https://doi.org/10.1016/j.jclepro.2022.135935
2. Bag, S., Gupta, S., Kumar, A., & Sivarajah, U. (2023). Role of digital technologies in supply chain resilience and sustainability. *International Journal of Production Economics, 255*, 108683. https://doi.org/10.1016/j.ijpe.2022.108683

3. Bressanelli, G., Adrodegari, F., Perona, M., & Saccani, N. (2023). Exploring the role of digital technologies to enable circular economy business models. *Sustainable Production and Consumption, 35*, 217–231.
4. Choi, T. Y., Rogers, D., & Vakil, B. (2023). Coronavirus is a wake-up call for supply chain management. *Harvard Business Review, 101*(1), 76–83.
5. Dutta, P., Choi, T. M., Somani, S., & Butala, R. (2024). Blockchain technology in supply chain operations: Applications, challenges, and future research directions. *Transportation Research Part E, 182*, 103355.
6. El Baz, J., & Ruel, S. (2024). Can supply chain risk management practices mitigate supply chain disruptions? *International Journal of Production Economics, 266*, 109021.
7. Ghadge, A., Wurtmann, H., & Seuring, S. (2023). Managing climate change risks in global supply chains. *International Journal of Production Research, 61*(9), 2851–2868.
8. Helo, P., & Hao, Y. (2023). Artificial intelligence in operations management and supply chain: A review. *Computers & Industrial Engineering, 175*, 108901.
9. Ivanov, D., & Dolgui, A. (2024). Digital supply chain twins for managing disruptions and sustainability. *Annals of Operations Research, 332*, 1–25.
10. Kache, F., & Seuring, S. (2023). Challenges and opportunities of digital information at the intersection of Big Data Analytics and supply chain management. *International Journal of Operations & Production Management, 43*(2), 223–250.
11. Kouhizadeh, M., Saberi, S., & Sarkis, J. (2024). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. *International Journal of Production Economics, 267*, 109070.
12. Luthra, S., Mangla, S. K., & Bag, S. (2023). Modeling enablers of digital transformation for sustainable supply chains. *Technological Forecasting and Social Change, 188*, 122290.
13. Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso Wamba, S. (2023). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid COVID-19. *Annals of Operations Research, 319*, 115–145.
14. Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2023). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research, 61*(7), 2109–2125.
15. Yadav, V. S., Singh, A. R., Gunasekaran, A., Raut, R. D., & Narkhede, B. E. (2024). Blockchain-enabled sustainable supply chain performance: A systematic review and future research directions. *Resources, Conservation & Recycling, 199*, 107210.
16. Bag, S., Gupta, S., Kumar, A., & Sivarajah, U. (2023). Role of digital technologies in supply chain resilience and sustainability. *International Journal of Production Economics, 255*, 108683. https://doi.org/10.1016/j.ijpe.2022.108683
17. Bressanelli, G., Adrodegari, F., Perona, M., & Saccani, N. (2023). Digital technologies for circular economy transition: A systematic review. *Sustainable Production and Consumption, 35*, 217–231.

Online ISSN: 3006-2047
Print ISSN: 3006-2039

18. Dutta, P., Choi, T. M., Somani, S., & Butala, R. (2024). Blockchain technology in supply chain operations: Applications and future research directions. *Transportation Research Part E: Logistics and Transportation Review, 182*, 103355.
19. El Baz, J., & Ruel, S. (2024). Supply chain risk management and disruption mitigation in the post-pandemic era. *International Journal of Production Economics, 266*, 109021.
20. Feng, Y., Lai, K. H., & Zhu, Q. (2022). Green supply chain innovation: Emergence, adoption, and challenges. *International Journal of Production Economics, 248*, 108497.
21. Ghadge, A., Wurtmann, H., & Seuring, S. (2023). Climate change risk management in global supply chains. *International Journal of Production Research, 61*(9), 2851–2868.
22. Helo, P., & Hao, Y. (2023). Artificial intelligence in operations management and supply chains: A structured literature review. *Computers & Industrial Engineering, 175*, 108901.
23. Ivanov, D., & Dolgui, A. (2024). Digital supply chain twins for managing resilience and sustainability. *Annals of Operations Research, 332*, 1–25.
24. Kamble, S. S., Gunasekaran, A., & Sharma, R. (2023). Blockchain-enabled sustainable supply chain performance: Empirical evidence from manufacturing firms. *Resources, Conservation & Recycling, 190*, 106822.
25. Kouhizadeh, M., Saberi, S., & Sarkis, J. (2024). Blockchain technology and sustainable supply chains: Adoption barriers and performance implications. *International Journal of Production Economics, 267*, 109070.
26. Luthra, S., Mangla, S. K., & Bag, S. (2023). Modeling enablers of digital transformation for sustainable supply chains. *Technological Forecasting and Social Change, 188*, 122290.
27. Mukhopadhyay, S., Singh, R. K., & Jain, T. (2024). Big data-enabled Marketing 4.0 framework for sustainable supply chain performance. *International Journal of Information Management Data Insights, 4*(1), 100214.
28. Parmentola, A., Petrillo, A., Tutore, I., & de Felice, F. (2022). Blockchain and environmental sustainability: A systematic review from the SDG perspective. *Business Strategy and the Environment, 31*, 194–217.
29. Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso Wamba, S. (2023). Impacts of epidemic outbreaks on supply chains: Research agenda and resilience insights. *Annals of Operations Research, 319*, 115–145.
30. Ren, Y., Wu, K. J., Lim, M. K., & Tseng, M. L. (2023). Technology transfer adoption to achieve circular economy under the resource-based view. *International Journal of Production Economics, 264*, 108983.
31. Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2023). Blockchain technology and sustainable supply chain management: Recent developments and future directions. *International Journal of Production Research, 61*(7), 2109–2125.

32. Sahebi, I. G., Mosayebi, A., Masoomi, B., & Marandi, F. (2022). Modeling enablers for blockchain adoption in renewable energy supply chains. *Technology in Society, 68*, 101871.
33. Samad, S., Nilashi, M., Almulihi, A., Alrizq, M., Alghamdi, A., & Mohd, S. (2023). Green supply chain management practices and firm performance: The moderating role of collaboration capability. *Technology in Society, 72*, 102183.
34. Yadav, V. S., Singh, A. R., Gunasekaran, A., Raut, R. D., & Narkhede, B. E. (2024). Blockchain-enabled sustainable supply chain performance: A systematic review. *Resources, Conservation & Recycling, 199*, 107210.
35. Zhang, Y., Sun, X., & Liu, Y. (2025). Digital transformation, blockchain integration, and sustainable supply chain performance: Evidence from emerging economies. *Journal of Cleaner Production, 430*, 139721.
36. Bag, S., Gupta, S., Kumar, A., & Sivarajah, U. (2023). Role of digital technologies in supply chain resilience and sustainability. *International Journal of Production Economics, 255*, 108683. https://doi.org/10.1016/j.ijpe.2022.108683
37. Bressanelli, G., Adrodegari, F., Perona, M., & Saccani, N. (2023). Digital technologies for circular economy transition: A systematic literature review. *Sustainable Production and Consumption, 35*, 217–231.
38. Dutta, P., Choi, T. M., Somani, S., & Butala, R. (2024). Blockchain technology in supply chain operations: Applications, challenges, and future research directions. *Transportation Research Part E: Logistics and Transportation Review, 182*, 103355.
39. El Baz, J., & Ruel, S. (2024). Supply chain risk management and resilience in the post-pandemic era. *International Journal of Production Economics, 266*, 109021.
40. Ghadge, A., Wurtmann, H., & Seuring, S. (2023). Climate change risk management in global supply chains: A review. *International Journal of Production Research, 61*(9), 2851–2868.
41. Helo, P., & Hao, Y. (2023). Artificial intelligence in operations management and supply chains: A structured literature review. *Computers & Industrial Engineering, 175*, 108901.
42. Ivanov, D., & Dolgui, A. (2024). Digital supply chain twins for managing resilience and sustainability. *Annals of Operations Research, 332*, 1–25.
43. Kamble, S. S., Gunasekaran, A., & Sharma, R. (2023). Blockchain-enabled sustainable supply chain performance: Empirical evidence from manufacturing firms. *Resources, Conservation & Recycling, 190*, 106822.
44. Kouhizadeh, M., Saberi, S., & Sarkis, J. (2024). Blockchain technology and sustainable supply chains: Adoption barriers and performance implications. *International Journal of Production Economics, 267*, 109070.
45. Luthra, S., Mangla, S. K., & Bag, S. (2023). Modeling enablers of digital transformation for sustainable supply chains. *Technological Forecasting and Social Change, 188*, 122290.

Online ISSN: 3006-2047
Print ISSN: 3006-2039

46. Mukhopadhyay, S., Singh, R. K., & Jain, T. (2024). Big data–enabled framework for sustainable supply chain performance. *International Journal of Information Management Data Insights, 4*(1), 100214.
47. Parmentola, A., Petrillo, A., Tutore, I., & de Felice, F. (2022). Blockchain and environmental sustainability: A systematic review from the SDG perspective. *Business Strategy and the Environment, 31*, 194–217.
48. Queiroz, M. M., Ivanov, D., Dolgui, A., & Wamba, S. F. (2023). Impacts of epidemic outbreaks on supply chains and resilience strategies. *Annals of Operations Research, 319*, 115–145.
49. Ren, Y., Wu, K. J., Lim, M. K., & Tseng, M. L. (2023). Technology adoption for circular economy practices under resource-based view. *International Journal of Production Economics, 264*, 108983.
50. Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2023). Blockchain technology and sustainable supply chain management: Recent developments. *International Journal of Production Research, 61*(7), 2109–2125.
51. Sahebi, I. G., Mosayebi, A., Masoomi, B., & Marandi, F. (2022). Blockchain adoption in renewable energy supply chains. *Technology in Society, 68*, 101871.
52. Samad, S., Nilashi, M., Almulihi, A., Alrizq, M., Alghamdi, A., & Mohd, S. (2023). Green supply chain management practices and firm performance: Moderating role of collaboration capability. *Technology in Society, 72*, 102183.
53. Yadav, V. S., Singh, A. R., Gunasekaran, A., Raut, R. D., & Narkhede, B. E. (2024). Blockchain-enabled sustainable supply chain performance: A systematic review. *Resources, Conservation & Recycling, 199*, 107210.
54. Zhang, Y., Sun, X., & Liu, Y. (2025). Digital transformation and sustainable supply chain performance in emerging economies. *Journal of Cleaner Production, 430*, 139721.
55. Zhao, X., Huo, B., Flynn, B. B., & Yeung, J. H. Y. (2023). The impact of supply chain integration on firm performance and sustainability outcomes. *Journal of Operations Management, 69*(6), 824–842.