Effects of Industry 4.0 on the triple bottom line of sustainability: the mediating role of healthcare green supply chain management

DOI: 10.46970/2025.31.1.06
Volume 31, *Number 1*
March, 2025, *pp. 122*-140

Ahmed Adnan Zaid
Department of Business Management, Palestine Technical University-Kadoorie, Tulkarm, Palestine.
Department of Management, College of Economics, Management & Information Systems, University of Nizwa, Nizwa, Oman
Email: ahmedzaid@unizwa.edu.om

Luay Jum'a
Department of Logistics Sciences, Business School, German Jordanian University, Amman, Jordan.
Email: Luay.juma@gju.edu.jo

Mohammad Sleimi
Department of Business Management, Palestine Technical University-Kadoorie, Tulkarm, Palestine.
Email: mohammad.sleimi@ptuk.edu.ps

Yahya Saleh
Department of Industrial and Mechanical Engineering, Faculty of Engineering, An-Najah National University, Nablus, Palestine.
Email: ysaleh@najah.edu

Ramiz Assaf *
Department of Industrial and Mechanical Engineering, Faculty of Engineering, An-Najah National University, Nablus, Palestine.
Email: ramizassaf@najah.edu

Bandar Altubaishe
Department of Supply Chain Management, College of Business Administration, University of Business and Technology, Jeddah 21448, Kingdom of Saudi Arabia.
Email: B.altubaishe@ubt.edu.sa

Abdalmuttaleb Al-Sartawi
Accounting, Finance and Banking Department, Ahlia University, Bahrain.
Email: amasartawi@hotmail.com

Salem Aljazzar
Industrial Engineering Department, Jeddah College of Engineering, University of Business and Technology, Jeddah 21448, Kingdom of Saudi Arabia.
Email: s.aljazzar@ubt.edu.sa

Siraj Zahran
Industrial Engineering Department, Jeddah College of Engineering, University of Business and Technology, Jeddah 21448, Kingdom of Saudi Arabia.
Email: s.zahran@ubt.edu.sa

Mohammad Kanan *
Industrial Engineering Department, Jeddah College of Engineering, University of Business and Technology, Jeddah 21448, Kingdom of Saudi Arabia.
Email: m.kanan@ubt.edu.sa

This study explores how Industry 4.0 technologies impact the environmental, social, and economic dimensions of sustainability in developing nations, with a focus on Palestine. It also examines the mediating role of green supply chain management practices in the healthcare sector in facilitating these outcomes. Adopting a quantitative research approach, data were collected through a structured questionnaire distributed to both administrative and clinical managers employed in private hospitals across Palestine, resulting in 131 valid survey responses. Partial least squares structural equation modelling was utilised to assess the latent constructs, examine reliability, and test the hypothesised relationships among the study variables. The analysis revealed a robust positive association between the adoption of Industry 4.0 technologies and the implementation of green supply chain management within healthcare institutions. Furthermore, both factors demonstrated significant positive influences on sustainability performance indicators across environmental, social, and economic dimensions. The results underscore the mediating function of green supply chain management practices in enabling Industry 4.0 technologies to contribute meaningfully to sustainability goals. This research offers valuable practical insights into the integration of technological advancements with environmentally responsible practices and outlines policy recommendations aimed at enhancing organisational sustainability in the healthcare sector.

Keywords: Healthcare Sector; Sustainability; Industrial Revolution; Triple Bottom Line; Healthcare Green Supply Chain Management.

Introduction

Sustainability within healthcare has garnered increasing scholarly attention in recent years, particularly in relation to financial governance, technological progress, service quality, and patient welfare (Swarnakar et al., 2023). This academic focus aligns with a broader global trend that supports the development of environmental management systems in medical institutions, a movement largely propelled by advances in medical technology, sophisticated equipment, and data analytics capabilities (Li & Carayon, 2021). The integration of information technologies and other contemporary innovations has emerged as a key approach to mitigating the environmental challenges inherent in the healthcare sector (Kuruvilla et al., 2023). At the same time, the concept of organisational sustainability—encompassing environmental, social, and economic domains—has acquired heightened importance across sectors, including healthcare, due to its capacity to generate long-term value (Braccini & Margherita, 2018).

Extant literature identifies various mechanisms through which sustainability performance can be enhanced, typically quantified by how environmental practices translate into measurable improvements in organisational ecological impact. The Triple Bottom Line (TBL), which comprises environmental, social, and economic sustainability metrics, remains the central paradigm for evaluating sustainable performance in organisational contexts (Hussain et al., 2018). The growing emphasis on sustainability compels healthcare institutions to refine management practices and align operational protocols with evolving stakeholder demands. In response, the sector has begun integrating Industry 4.0 (I4.0) technologies into core functions, recognising their capacity to bolster competitive advantage through sustainability-driven innovation (Tortorella et al., 2024). These technologies enable more efficient use of resources, reduce energy consumption, and minimise waste and carbon emissions across production and supply chain operations (Ghadge et al., 2022). As such, the digital transformation of healthcare, marked by increasing adoption of digital systems and interoperable data flows, has become a strategic imperative for health service providers.

Despite the global relevance of I4.0, its uptake in low- and middle-income countries remains limited (Sibanda et al., 2022). Nevertheless, its transformative potential for enhancing sustainability in resource-constrained settings is profound. Adoption is often hindered by financial constraints and insufficient technical expertise (Mwanza et al., 2023; Tortorella et al., 2024; Ziyadeh et al., 2023). Moreover, the ecological impact of healthcare delivery—primarily via supply chain operations—necessitates improved environmental performance (Benzidia et al., 2021). In the context of Palestine, hospitals generate substantial volumes of hazardous medical waste, with estimates suggesting an average of 0.78 kg per hospital bed daily, ranging from 0.54 to 1.82 kg (Al-Khatib et al., 2020). This context highlights the pressing need for environmentally responsible practices. Tackling environmental issues amid uncertainty requires robust and sustainable supply chain models (Chatterjee et al., 2023). Healthcare Green Supply Chain Management (HC-GSCM) offers one such approach, incorporating green procurement, sustainable production, eco-logistics, and reverse logistics. These practices are intended to support environmental conservation, promote social responsibility, and enhance cost efficiency while maintaining high standards of patient care (Abaku & Odimarha, 2024).

For the healthcare sector to institutionalise sustainability, regulatory and policy frameworks must prioritise environmental goals. Recent advancements in Palestine's digital infrastructure, such as expanded internet access and fibre optic networks, create favourable conditions for I4.0 integration (Demaidi, 2023). As a result, I4.0 technologies are increasingly recognised as drivers of sustainable development and economic growth in healthcare. However, resource-constrained environments face persistent challenges, with local factors significantly affecting I4.0's effectiveness (Ilangakoon et al., 2022). Although I4.0 adoption has been widely studied in manufacturing (Riaz et al., 2025), limited empirical research addresses its role in sustainable healthcare supply chains (Aslam et al., 2021; Liu et al., 2023). There is a growing need to examine the interaction between I4.0, HC-GSCM, and TBL outcomes (Paul et al., 2021). It is suggested that I4.0 supports the adoption of HC-GSCM, which subsequently mediates improvements in sustainability performance. Nonetheless, this triadic relationship remains insufficiently explored, particularly in developing countries such as Palestine (Ghadge et al., 2022; Maria Aslam & Siddiqui, 2023).

In response to these gaps, the present study offers three key contributions. First, it investigates the synergistic effects of I4.0, HC-GSCM, and TBL on the broader sustainability agenda within healthcare. Second, it contributes empirical insights from a developing country where integration of green supply chain principles and I4.0 is minimal (Kholaif et al., 2023). Third, employing the perspective of the Practice-Based View (PBV) theory, the study explores how I4.0 facilitates the implementation of HC-GSCM practices, ultimately enhancing environmental, economic, and social sustainability performance. Accordingly, the study is guided by the following research questions:

1. In what ways do Industry 4.0 technologies influence the adoption and functional efficiency of HC-GSCM practices?
2. How does the integration of Industry 4.0 technologies into HC-GSCM impact sustainability across environmental, economic, and social dimensions?
3. To what extent does HC-GSCM act as an intermediary in linking Industry 4.0 technologies with Triple Bottom Line performance outcomes?

Literature Review and Hypothesis Development

Theoretical Foundation

This study applies PBV to investigate the pivotal role of digital technologies in enhancing HC-GSCM practices and their resultant impact on organisational sustainability performance. According to PBV, organisational performance differences can be attributed to the adoption of transferable and replicable practices that are applicable across diverse institutional settings. Within this framework, sustainability performance is conceptualised as the dependent variable, while adaptable operational practices, supported by digital innovation, function as the independent variables (Treacy et al., 2019). PBV asserts that the strategic integration of such practices contributes to performance differentiation among firms. The current study extends existing discourse on I4.0 and green supply chain initiatives by applying PBV to examine how digital technologies facilitate the adoption of HC-GSCM and support improvements in sustainability outcomes. Prior research utilising PBV has effectively evaluated supply chain strategies under conditions such as environmental disruptions. Drawing from this body of literature, the study identifies prominent green practices and develops an evaluative framework to explore the extent to which I4.0 enables the implementation of HC-GSCM, thereby promoting enhanced sustainability performance (Bromiley & Rau, 2014).

I4.0 Technologies and Sustainability Performance

In the contemporary competitive landscape, organisations across diverse sectors are increasingly integrating sustainability objectives with the capabilities of I4.0. The deployment of advanced, cleaner, and more efficient technological innovations has emerged as a critical enabler of long-term organisational viability and competitiveness (Braccini & Margherita, 2018). Within the healthcare context, I4.0 has notably improved service accessibility in underserved regions while simultaneously enhancing the financial resilience of hospitals through increased patient throughput (Meiling et al., 2021). These advancements have contributed to both social and economic sustainability without compromising environmental resource conservation. Furthermore, the application of big data analytics has been shown to bolster the environmental performance of healthcare institutions, as evidenced in the Indian context (Kumar & Chakraborty, 2022). Collectively, these findings support the contention that I4.0 facilitates the strategic alignment of internal environmental processes with external supplier networks, thereby reinforcing its influence on all three dimensions of the triple bottom line (Kamble et al., 2018).

I4.0 Technologies and Healthcare-GSCM

The healthcare sector is undergoing a shift as Industry 4.0 drives the digital integration of manufacturing and supply chain processes. This paradigm shift carries profound implications for supply chain management, particularly in relation to sustainability practices. The realisation of a sustainable healthcare supply chain necessitates the coordinated interaction among information systems, suppliers, service providers, internal and external customers, and end-users (Beier et al., 2022; Scavarda et al., 2019). The deployment of digital tools under I4.0 enhances supply chain efficiency, thereby exerting a positive influence on the operational dynamics of the healthcare domain (Kuruvilla et al., 2023). A key advantage of I4.0 lies in its capacity to improve supply chain visibility and traceability, enabling decision-makers to adopt eco-efficient solutions such as autonomous vehicles for extended logistics operations, which mitigates carbon emissions and alleviates driver workload (Liu et al., 2023).

Furthermore, I4.0 has compelled organisations to reformulate strategic planning with an increased emphasis on financial robustness, as well as broader environmental and social sustainability objectives (Carole et al., 2023). This integration is widely perceived as a synergistic opportunity wherein both operational performance and sustainability outcomes are concurrently advanced. Technological innovation thus emerges as an indispensable catalyst in attaining sustainable goals (Lodhi et al., 2024). The unique capabilities of I4.0 foster process integration, waste reduction, and the generation of value across various industrial sectors (Söderholm, 2013). By leveraging these tools, firms can enhance sustainable performance through streamlined workflows, adherence to ethical and transparent standards, and automation that boosts operational efficiency. Additionally, big data analytics accelerate the pursuit of sustainability by providing timely and actionable insights (Ashraf et al., 2022).

Healthcare-GSCM and Sustainability Performance

In the provision of healthcare services, inefficient utilisation or mismanagement of medical resources can exert undue pressure on natural ecosystems (Thind et al., 2021). In response, the development of HC-GSCM has emerged as a theoretical construct encompassing a suite of strategies aimed at mitigating the ecological footprint associated with healthcare goods and services (Govindan et al., 2020). Scholars posit that HC-GSCM fosters environmental sustainability by minimising waste generation and operational inefficiencies within healthcare institutions. Furthermore, extant literature highlights that environmentally conscious practices can yield measurable financial advantages for healthcare providers (Schleper et al., 2021). For instance, HC-GSCM is linked to tangible benefits such as reductions in waste volumes and energy expenditures, thereby generating direct economic value for healthcare organisations. In addition, intangible financial gains can also accrue through enhanced patient satisfaction, loyalty, and favourable public perception, as institutions incorporating green practices often experience improved stakeholder engagement (Yildiz Çankaya & Sezen, 2019).

This study specifically investigates the mediating role of HC-GSCM in the relationship between I4.0 technologies and the TBL components of sustainability. Empirical research substantiates that I4.0 significantly facilitates the deployment of healthcare-specific controls within green supply chain frameworks, which in turn improves environmental performance (Kros et al., 2019; Wang et al., 2020). Beyond environmental impacts, I4.0 strengthens logistical efficiency, enhances communication infrastructures, and lowers operational expenditures, thereby supporting economic advancement and fostering innovative modes of healthcare delivery (Albarune et al., 2015; Scavarda et al., 2019). Through I4.0 integration, healthcare organisations can establish agile, interconnected value chains while simultaneously elevating overall supply chain performance (Hossain & Thakur, 2021). Technologies such as predictive analytics allow for accurate forecasting of patient inflows, which optimises inventory control and curtails waste arising from overstocked or expired medical supplies. Moreover, I4.0 enables route optimisation to curtail fuel usage and emissions, ultimately reducing transportation expenses (Allahham et al., 2023). Collectively, these capabilities contribute to cleaner production processes and reinforce the sustainability trajectory of healthcare supply chains.

Research Methodology

Research Approach

This study adopted a quantitative approach to test the proposed model and examine relationships among key constructs using PLS-SEM. Data were gathered via a structured survey targeting administrative staff and healthcare managers from 41 private hospitals in the West Bank, focusing solely on the private healthcare sector. Fieldwork took place in December 2024, with support from the Palestinian Ministries of Health and Labour to ensure regulatory compliance. Survey validity was confirmed through expert review by seven academics and five supply chain professionals, assessing clarity, content relevance, and scale suitability. Of the 170 questionnaires disseminated, 131 were returned fully completed after a two-month period, yielding a response rate of 77%. The survey employed a five-point Likert scale, ranging from 1 (minimal agreement) to 5 (maximum agreement), to capture respondent perceptions. The findings substantiate the considerable potential of I4.0 in advancing sustainability outcomes within healthcare systems through the implementation of HC-GSCM. The study's conceptual model, illustrated in Figure 1, visually represents the interactive dynamics between I4.0 technologies and HC-GSCM in influencing TBL dimensions of sustainability.

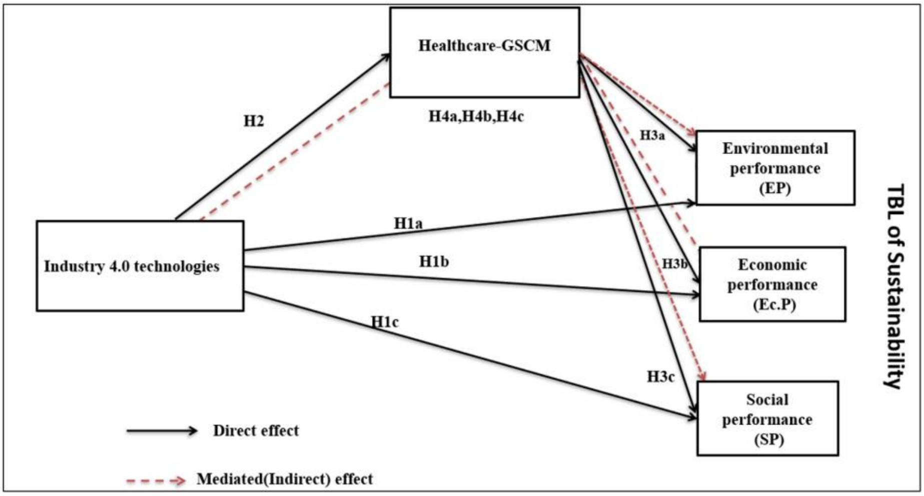

Figure 1: *Estimated Model*

Measurements

To establish construct validity, the questionnaire items were adapted from authoritative sources within the existing literature. The scale measuring I4.0 comprised six foundational technological dimensions, based on the frameworks proposed by Aceto et al. (2020), Batko and Ślęzak (2022), Alowais et al. (2023), and Javaid and Haleem (2019). The construct of HC-GSCM was operationalised through five measurement items, sourced from the validated instruments developed by Vishwakarma et al. (2023) and Kholaif et al. (2023). Sustainability performance, encompassing environmental performance (EP), social performance (SP), and economic performance (Ec.P), was evaluated using a set of 12 items, equally distributed across the three dimensions, derived from Saha et al. (2022) and AlQershi et al. (2022). A comprehensive list of the measurement items employed is provided in Table 1.

Findings

Respondent Profiles

The dataset underpinning this study was obtained from administrative personnel and healthcare managers operating within private hospitals throughout Palestine. The respondent cohort was composed of managers (45.3%), team leaders (37.5%), and front-line staff (17.2%). A substantial proportion (over 78%) of participants were affiliated with large-scale healthcare institutions, indicating the representativeness of the sample in terms of organisational size. Regarding educational attainment, the majority held undergraduate qualifications (BSc or BA), while slightly more than 22% reported holding postgraduate degrees (MSc). Moreover, the robustness of the dataset is reinforced by the fact that 62% of respondents reported at least a decade of professional experience in the healthcare sector, thereby contributing to the dependability and analytical rigour of the survey results.

Table 1: *Factor Loading Analysis*

Constructs	Item	Indicator	Factor Loadings	Cronbach Alpha Value (α)	CR	AVE
Industry 4.0 Technologies	Artificial intelligence systems identify patterns, analyse patient data, and predict their health state.	I4.0-1	0.751	0.898	0.923	0.667
	Big data analytics handles massive volumes of patient data, including electronic health records and medical imaging.	I4.0-2	0.684			
	Cloud computing allows for secure storage and remote access to patient data, as well as collaboration on treatment regimens that improve the health of patients.	I4.0-3	0.869			
	Implement a modern security method protecting patient data from cyber-attacks while maintaining data privacy.	I4.0-4	0.902			
	Our organization applied virtual reality technology in training employees and improving patient education.	I4.0-5	0.875			
	To deliver telehealth services, the hospital using telemedicine, that includes digital technology for example video conferencing and remote monitoring.	I4.0-6	0.7			
Healthcare-GSCM (HC-GSCM)	Decreasing the existence of counterfeit medical manufactured goods.	HC-GSCM-1	0.734	0.913	0.936	0.747
	Involve suppliers in sustainable activities, such as conducting environmental audits and using green criteria for supplier selection.	HC-GSCM-2	0.924			
	Sharing information helps reduce unethical practices, such as corruption, thereby contributing to the enhancement of social sustainability.	HC-GSCM-3	0.915			
	Environmental considerations are integrated into procurement activities.	HC-GSCM-4	0.881			
	Our organization has implemented environmental management systems to comply with ISO standards.	HC-GSCM-5	0.854			

Table 1(continued): *Factor Loading Analysis*

Constructs	Item	Indicator	Factor Loadings	Cronbach Alpha Value (α)	CR	AVE
Economic Performance (Ec.P)	A decrease in waste treatment and disposal costs.	EcP-1	0.878	0.895	0.927	0.761
	Lowering energy consumption costs in the hospital.	EcP-2	0.844			
	A growth in the hospital's market share.	EcP-3	0.755			
	Increasing hospital profits is often a result of lowering material and energy consumption.	EcP-4	0.803			
Environmental Performance (EP)	The hospital is working to reduce both direct and indirect toxic waste.	EP-1	0.759	0.800	0.870	0.626
	Efforts are being made to reduce and recycle hospital waste.	EP-2	0.844			
	The hospital is increasing its purchase of environmentally friendly products.	EP-3	0.755			
	There are safeguards in place to prevent incidents such as hazardous material mismanagement, poisoning, and radioactive leaks.	EP-4	0.803			
Social Performance (SP)	Reduces the negative impact of waste from hospitals on communities nearby.	SP-1	0.919	0.846	0.897	0.685
	Increasing awareness of regulations that protect workers' health and safety.	SP-2	0.773			
	Enhancing the hospital's reputation while improving community health and safety and limiting the spread of infections.	SP-3	0.792			
	Improving healthcare quality of service whilst conforming to the ethical standards of morals.	SP-4	0.820			

Data Analysis

The questionnaire data were subjected to analysis using PLS-SEM, implemented through SmartPLS version 3.9, to examine the interrelations among the proposed constructs. The analytical procedure was executed in two sequential phases. In the first phase, the measurement model was scrutinised to ascertain the reliability and validity of the constructs. Subsequently, the structural model was assessed to evaluate the hypothesised causal linkages within the proposed theoretical framework.

Measurement Model Analysis

Convergent validity was verified through factor loadings, AVE, and CR, following established criteria (Ramayah et al., 2018). All loadings, Cronbach's alpha, and CR values exceeded 0.70, with CR ranging from 0.870 to 0.936, confirming internal consistency (Hair et al., 2019). AVE values (0.626–0.761) surpassed the 0.50 threshold, as shown in Table 1 and illustrated in Figure 2. Discriminant validity, assessed using the Fornell-Larcker criterion and HTMT ratio, met the required threshold of below 0.90, with only slight, acceptable deviations noted in Table 2 (Fornell & Larcker, 1981; Henseler et al., 2015).

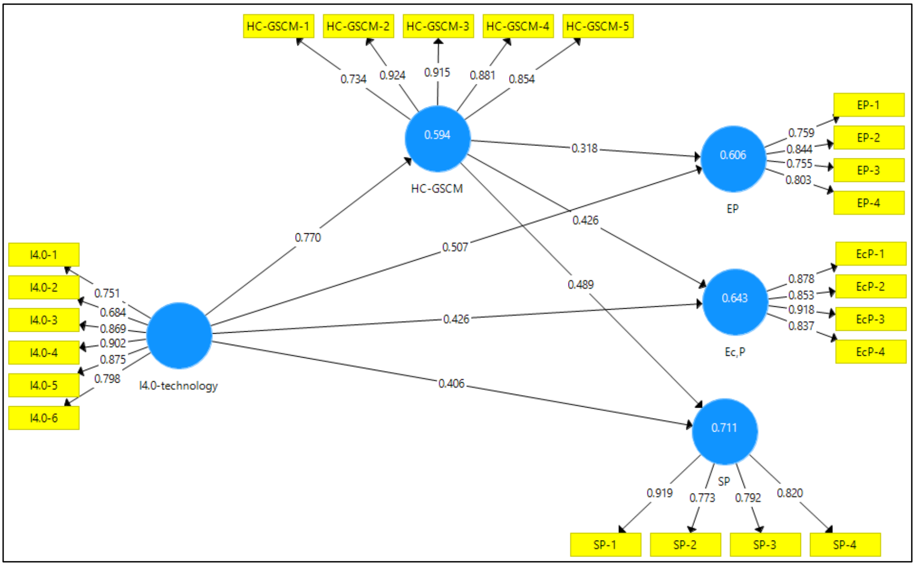

Figure 2: *Measurement Model*

Table 2: *Discriminant Validity*

Fornell and Larcker	EP	EcP	HC-GSCM	I4.0	SP
EP	**0.791**				
EcP	0.621	**0.872**			
HC-GSCM	0.508	0.554	**0.864**		
I4.0	0.652	0.754	0.770	**0.817**	
SP	0.567	0.480	0.477	0.640	**0.828**

Table 2(continued): *Discriminant Validity*

HTMT	EP	EcP	HC-GSCM	I4.0	SP
EP					
EcP	0.670				
HC-GSCM	0.707	0.622			
I4.0	0.688	0.644	0.802		
SP	0.607	0.556	0.560	0.566	

Structural Model Analysis

The explanatory strength of R^2 is conventionally categorised as strong (≥0.75), moderate (≥0.50), or weak (≥0.25). In this study, I4.0 and HC-GSCM jointly demonstrated a moderate explanatory influence on EP and Ec.P, with R^2 values of 0.606 and 0.643, respectively. A stronger effect was noted for SP, where R^2 reached 0.711. For HC-GSCM, an R^2 of 0.594 indicated that I4.0 alone accounted for 59.4% of its variance, reflecting a moderate effect. These results are summarised in Table 3 and illustrated in Figure 2. Effect sizes (f^2), used to assess the unique contribution of each construct and interpreted using Cohen (1988) guidelines (small = 0.02, medium = 0.15, large = 0.35), showed that I4.0 had moderate effects on EP (f^2 = 0.265), Ec.P (f^2 = 0.207), and SP (f^2 = 0.232), and a substantial effect on HC-GSCM (f^2 = 1.460). HC-GSCM itself exerted moderate effects on EP (f^2 = 0.105), Ec.P (f^2 = 0.206), and SP (f^2 = 0.336).

Table 3: *Endogenous Construct using Q2 Statistics*

Construct	R^2	f^2 HC-GSCM	f^2 Industry 4.0	Q^2 Predict	Variance Inflation Factor (VIF)
EP	0.606	0.105	0.265	0.290	1.690
Ec.P	0.634	0.206	0.207	0.257	1.000
HC-GSCM	0.594	----	1.460	0.452	1.680
SP	0.711	0.336	0.232	0.367	1.970

Complete values for R^2, f^2, Q^2, and VIF are presented in Table 3. VIF values for the eight latent constructs ranged from 1.06 to 2.05, remaining well below the conventional cut off of 3, thus confirming no multicollinearity. The SRMR value of 0.075 fell below the recommended threshold by Hu and Bentler (1998), indicating a satisfactory model fit. Due to residual non-normality, the PLS algorithm with bootstrapping was used to estimate the structural relationships. In PLS-SEM, the significance and alignment of path coefficients with hypothesised directions determine whether each hypothesis is supported or rejected.

Finally, the PLS algorithm was applied to estimate the hypothesised relationships using the bootstrapping technique. In the context of PLS-SEM, the assessment of path coefficients is pivotal, as their statistical significance and consistency with the hypothesised directions determine the extent to which each hypothesis is supported or refuted. The bootstrapping procedure, based on 5,000 resamples, produced empirical estimates for both direct and indirect effects, including path coefficients (β), standard deviations, t-values, and p-values. These results are thoroughly reported in Table 4. Moreover, Table 4 provides robust empirical evidence supporting the hypothesised relationships among I4.0, HC-GSCM, and the three sustainability dimensions outlined within the TBL framework. The statistical outcomes confirmed the significance of all proposed hypotheses, with results as follows: H1a (β = 0.507, t = 3.876, p = 0.000), H1b (β = 0.426, t = 3.636, p = 0.000), H1c (β = 0.406, t = 4.184, p = 0.000), H2 (β = 0.770, t = 15.851, p = 0.000), H3a (β = 0.318, t = 2.214, p = 0.027), H3b (β = 0.426, t = 3.435, p = 0.001), and H3c (β = 0.489, t = 4.886, p = 0.000).

Table 4: *Hypothesis Testing*

No.	Hypothesis	Original Sample (O)	Sample Mean (M)	Standard Deviation	T Stats	P Values	Decision
H1a	I4.0 -> EP	0.507	0.501	0.131	3.876	0.000	Supported
H1b	I4.0 -> EcP	0.426	0.424	0.117	3.636	0.000	Supported
H1c	I4.0 -> SP	0.406	0.418	0.097	4.184	0.000	Supported
H2	I4.0 -> HC-GSCM	0.770	0.769	0.049	15.851	0.000	Supported
H3a	HC-GSCM -> EP	0.318	0.322	0.144	2.214	0.027	Supported
H3b	HC-GSCM -> EcP	0.426	0.427	0.124	3.435	0.001	Supported
H3c	HC-GSCM -> SP	0.489	0.481	0.100	4.886	0.000	Supported

Note: t >1.96 ** ($p < 0.05$); t > 2.57 *** ($p < 0.01$).

To assess the mediating role of HC-GSCM, a mediation framework was employed that requires a statistically significant indirect effect (a×b) to confirm mediation. Full mediation is concluded when the direct effect (c-path) becomes non-significant, while complementary partial mediation is indicated if all paths (a, b, and the adjusted c̄) are significant and directionally consistent. Conversely, if the direction of c̄ differs from paths a and b, competitive mediation is inferred. Bootstrapping results presented in Table 5 confirmed the mediating influence of HC-GSCM in the relationship between I4.0 and the TBL dimensions. Statistically significant indirect effects were found for EP (β = 0.245, 95% CI: 0.03–0.479), Ec.P (β = 0.328, 95% CI: 0.148–0.536), and SP (β = 0.377, 95% CI: 0.206–0.547). The continued significance and directional alignment of both direct and indirect effects support the existence of complementary partial mediation, thereby validating hypotheses H4a, H4b, and H4c.

Table 5: *Hypothesis testing of Moderating Effects*

HYPOTHESIS	A	B	C̄	POINT ESTIMATE	INDIRECT EFFECT 95% CI		DECISION
					LCL	UCL	
H4A: I4.0 -> HC-GSCM -> EP	0.770	0.318	0.507	0.245	0.03	0.479	Partial Mediation
H4B: I4.0 -> HC-GSCM -> ECP	0.770	0.426	0.329	0.328	0.148	0.536	Partial Mediation
H4C: I4.0 -> HC-GSCM -> SP	0.770	0.489	0.406	0.377	0.206	0.547	Partial Mediation

Note: LCL denotes lower and upper confidence limits, while UCL denotes upper confidence limits.

Discussion

Environmental degradation continues to pose significant threats to ecosystems and the global climate. In response, growing pressure from diverse stakeholders has prompted healthcare institutions to integrate ecological strategies with I4.0 technologies. This integration aims to enhance operational efficiency, reduce energy consumption, minimise pollution, and advance sustainability objectives. The present study reveals a significant positive relationship between I4.0 technologies and the TBL dimensions—EP, Ec.P, and SP—corroborating prior research that established similar links (Cricelli et al., 2024).

I4.0 facilitates efficient data management and supports the adoption of GSCM practices within healthcare settings. It serves as a strategic enabler for embedding sustainability into procurement processes, supplier assessments, and green auditing procedures, thereby aligning environmentally responsible practices with existing operational systems (Asokan et al., 2022; Sony, 2019). Empirical evidence also indicates that these technologies enhance employee morale and reduce workplace accidents (Saha et al., 2022). The current findings reinforce earlier observations of a strong influence of I4.0 on HC-GSCM (Kholaif et al., 2023; Vishwakarma et al., 2023), and demonstrate how blockchain-based applications can strengthen various SCM functions, enhancing operational efficiency (Kouhizadeh et al., 2021).

Furthermore, the study confirms the mediating role of HC-GSCM in the relationship between I4.0 and sustainability performance, identifying I4.0 as a key driver of continuous technological and operational improvement. The integration of digital control systems within the healthcare sector has not only improved service quality but also enhanced profitability, as previously documented (Wu et al., 2006). However, limited research has examined how HC-GSCM mediates the influence of I4.0 on social, environmental, and economic outcomes. This study positions HC-GSCM as an effective model for aligning I4.0-driven innovations with strategic sustainability objectives. The digital transformation of HC-GSCM offers a robust infrastructure for embedding green supply chain initiatives, supported by advancements in information and computerised technologies. Overall, the findings affirm that I4.0 contributes to long-term sustainability both directly and indirectly, with the latter effect mediated by HC-GSCM.

Research Implications

This study offers significant theoretical contributions that merit further investigation, particularly in highlighting the notable impact of I4.0 technologies on the implementation of HC-GSCM practices—an area that has been relatively underexplored in current academic literature. The confirmed relationship between these constructs supports the call for continued empirical research to enrich understanding in this field. While previous studies have only marginally addressed the role of I4.0 in promoting sustainability within the healthcare sector, especially in low-income regions such as Palestine, this research is among the few that specifically focuses on this context. The integration of GSCM with I4.0 is shown to substantially elevate sustainability outcomes in the Palestinian healthcare system.

From a practical perspective, healthcare providers are encouraged to prioritise the strategic embedding of environmentally sustainable practices within their supply chain networks (Govindan et al., 2020). With rising accountability pressures, organisations must now address both environmental and social responsibilities across the entire supply chain. The institutionalisation of GSCM within healthcare settings has enabled organisations to respond more effectively to environmental concerns raised by patients and stakeholders, particularly during crises such as pandemics and other disruptive events. The implementation of HC-GSCM practices enhances the capacity of service providers to meet public expectations for sustainable healthcare delivery. Moreover, recognising the mediating role of HC-GSCM equips decision-makers with the foresight needed to anticipate potential barriers to sustainability advancement, thereby reducing the risk of costly implementation failures. These findings demonstrate that top management can significantly improve healthcare service delivery by adopting HC-GSCM and leveraging I4.0 technologies to align operational efficiency with long-term sustainability goals.

Conclusion

The primary objective of this study is to assist hospital administrators in enhancing sustainability performance through the integration of GSCM practices. Grounded within the PBV theoretical framework, the research investigates the mediating role of HC-GSCM in the relationship between I4.0 implementation and the sustainability dimensions defined by the TBL model. This inquiry addresses a clear gap in the literature regarding the influence of I4.0 technologies on hospital sustainability, particularly in relation to HC-GSCM. Data were collected via structured surveys administered in private healthcare institutions located in the West Bank, targeting managers across various hierarchical levels. This methodological approach provides a holistic view of organisational practices and strategic orientations. The findings offer original empirical insights into the adoption of HC-GSCM strategies and the integration of I4.0 technologies within the healthcare sector—an area that remains insufficiently examined in existing scholarship. For healthcare institutions in Palestine seeking to improve their sustainability outcomes, the successful application of I4.0 technologies—such as cloud computing, big data analytics, and the Internet of Things—must be supported by a firm organisational commitment to enhancing operational procedures through HC-GSCM frameworks.

References

Abaku, E. A., & Odimarha, A. C. (2024). Sustainable supply chain management in the medical industry: a theoretical and practical examination. *International Medical Science Research Journal*, *4*(3), 319-340. https://doi.org/10.51594/imsrj.v4i3.931

Aceto, G., Persico, V., & Pescapé, A. (2020). Industry 4.0 and health: Internet of things, big data, and cloud computing for healthcare 4.0. *Journal of Industrial Information Integration*, *18*, 100129. https://doi.org/10.1016/j.jii.2020.100129

Al-Khatib, I. A., Khalaf, A.-S., Al-Sari, M. I., & Anayah, F. (2020). Medical waste management at three hospitals in Jenin district, Palestine. *Environmental Monitoring and Assessment*, *192*(1), 10. https://doi.org/10.1007/s10661-019-7992-0

Albarune, A. R. B., Farhat, N., & Afzal, F. (2015). Valued supply chain for integrated hospital management: A conceptual framework. *International Journal of*

Supply Chain Management, *4*(3), 39-49. https://core.ac.uk/download/pdf/230742533.pdf

Allahham, M., Sharabati, A.-A. A., Hatamlah, H., Ahmad, A. Y. B., Sabra, S., & Daoud, M. K. (2023). Big data analytics and AI for green supply chain integration and sustainability in hospitals. *WSEAS Transactions on Environment and Development*, *19*, 1218-1230. https://doi.org/10.37394/232015.2023.19.111

Alowais, S. A., Alghamdi, S. S., Alsuhebany, N., Alqahtani, T., Alshaya, A. I., Almohareb, S. N., Aldairem, A., Alrashed, M., Bin Saleh, K., & Badreldin, H. A. (2023). Revolutionizing healthcare: the role of artificial intelligence in clinical practice. *BMC medical education*, *23*(1), 689. https://doi.org/10.1186/s12909-023-04698-z

AlQershi, N. A., Thurasamy, R., Ali, G. A., Al-Rejal, H. A., Al-Ganad, A., & Frhan, E. (2022). The effect of talent management and human capital on sustainable business performance: An empirical investigation in Malaysian hospitals. *International Journal of Ethics and Systems*, *38*(2), 316-337. https://doi.org/10.1108/IJOES-06-2021-0130

Ashraf, R., Khan, M. A., Khuhro, R. A., & Bhatti, Z. A. (2022). Knowledge creation dynamics of technological forecasting and social change special issues. *Technological Forecasting and Social Change*, *180*, 121663. https://doi.org/10.1016/j.techfore.2022.121663

Aslam, J., Saleem, A., Khan, N. T., & Kim, Y. B. (2021). Factors influencing blockchain adoption in supply chain management practices: A study based on the oil industry. *Journal of Innovation & Knowledge*, *6*(2), 124-134. https://doi.org/10.1016/j.jik.2021.01.002

Asokan, D. R., Huq, F. A., Smith, C. M., & Stevenson, M. (2022). Socially responsible operations in the Industry 4.0 era: post-COVID-19 technology adoption and perspectives on future research. *International Journal of Operations & Production Management*, *42*(13), 185-217. https://doi.org/10.1108/IJOPM-01-2022-0069

Batko, K., & Ślęzak, A. (2022). The use of Big Data Analytics in healthcare. *Journal of big Data*, *9*(1), 3. https://doi.org/10.1186/s40537-021-00553-4

Beier, G., Matthess, M., Shuttleworth, L., Guan, T., Grudzien, D. I. d. O. P., Xue, B., De Lima, E. P., & Chen, L. (2022). Implications of Industry 4.0 on industrial employment: A comparative survey from Brazilian, Chinese, and German practitioners. *Technology in society*, *70*, 102028. https://doi.org/10.1016/j.techsoc.2022.102028

Benzidia, S., Makaoui, N., & Bentahar, O. (2021). The impact of big data analytics and artificial intelligence on green supply chain process integration and hospital environmental performance. *Technological Forecasting and Social Change*, *165*, 120557. https://doi.org/10.1016/j.techfore.2020.120557

Braccini, A. M., & Margherita, E. G. (2018). Exploring organizational sustainability of industry 4.0 under the triple bottom line: The case of a manufacturing company. *Sustainability*, *11*(1), 36. https://doi.org/10.3390/su11010036

Bromiley, P., & Rau, D. (2014). Towards a practice-based view of strategy. *Strategic Management Journal*, *35*(8), 1249-1256. https://doi.org/10.1002/smj.2238

Carole, K. S., Mohapatra, B., Tripathy, S., Singhal, D., Joo, M. I., & Kim, H.-C. (2023). A Sustainable Supply Chain Management Framework using Industry 4.0

Technologies in the Healthcare Sector: A Comprehensive Review. https://doi.org/10.20944/preprints202311.1343.v1

Chatterjee, S., Chaudhuri, R., Gupta, S., Mangla, S. K., & Kamble, S. (2023). Examining the influence of industry 4.0 in healthcare supply chain performance: Moderating role of environmental dynamism. *Journal of cleaner production*, *427*, 139195. https://doi.org/10.1016/j.jclepro.2023.139195

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale. Erlbaum. https://doi.org/10.4324/9780203771587

Cricelli, L., Mauriello, R., Strazzullo, S., & Camilleri, M. A. (2024). Assessing the impact of Industry 4.0 technologies on the social sustainability of agrifood companies. *Business Strategy and the Environment*, *33*(7), 7182-7200. https://doi.org/10.1002/bse.3874

Demaidi, M. N. (2023). Artificial intelligence national strategy in a developing country. *Ai & Society*, 1-13. https://doi.org/10.1007/s00146-023-01779-x

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of marketing research*, *18*(1), 39-50. https://doi.org/10.1177/002224378101800104

Ghadge, A., Mogale, D. G., Bourlakis, M., Maiyar, L. M., & Moradlou, H. (2022). Link between Industry 4.0 and green supply chain management: Evidence from the automotive industry. *Computers & Industrial Engineering*, *169*, 108303. https://doi.org/10.1016/j.cie.2022.108303

Govindan, K., Mina, H., & Alavi, B. (2020). A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19). *Transportation Research Part E: Logistics and Transportation Review*, *138*, 101967. https://doi.org/10.1016/j.tre.2020.101967

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. *European business review*, *31*(1), 2-24. https://doi.org/10.1108/EBR-11-2018-0203

Henseler, J., Ringle, C. M., & Sarstedt, M. (2015). A new criterion for assessing discriminant validity in variance-based structural equation modeling. *Journal of the academy of marketing science*, *43*(1), 115-135. https://doi.org/10.1007/s11747-014-0403-8

Hossain, M. K., & Thakur, V. (2021). Benchmarking health-care supply chain by implementing Industry 4.0: a fuzzy-AHP-DEMATEL approach. *Benchmarking: An International Journal*, *28*(2), 556-581. https://doi.org/10.1108/BIJ-05-2020-0268

Hu, L.-t., & Bentler, P. M. (1998). Fit indices in covariance structure modeling: Sensitivity to underparameterized model misspecification. *Psychological methods*, *3*(4), 424. https://doi.org/10.1037//1082-989x.3.4.424

Hussain, N., Rigoni, U., & Orij, R. P. (2018). Corporate governance and sustainability performance: Analysis of triple bottom line performance. *Journal of business ethics*, *149*(2), 411-432. https://doi.org/10.1007/s10551-016-3099-5

Ilangakoon, T. S., Weerabahu, S. K., Samaranayake, P., & Wickramarachchi, R. (2022). Adoption of Industry 4.0 and lean concepts in hospitals for healthcare operational performance improvement. *International Journal of Productivity* *and Performance Management*, *71*(6), 2188-2213. https://doi.org/10.1108/IJPPM-12-2020-0654

Javaid, M., & Haleem, A. (2019). Industry 4.0 applications in medical field: A brief review. *Current Medicine Research and Practice*, *9*(3), 102-109. https://doi.org/10.1016/j.cmrp.2019.04.001

Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2018). Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process safety and environmental protection*, *117*, 408-425. https://doi.org/10.1016/j.psep.2018.05.009

Kholaif, M. M. N. H. K., Xiao, M., & Tang, X. (2023). Opportunities presented by COVID-19 for healthcare green supply chain management and sustainability performance: The moderating effect of social media usage. *IEEE Transactions on Engineering Management*, *71*, 4441-4454. https://doi.org/10.1109/TEM.2023.3239504

Kouhizadeh, M., Saberi, S., & Sarkis, J. (2021). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. *International journal of production economics*, *231*, 107831. https://doi.org/10.1016/j.ijpe.2020.107831

Kros, J. F., Kirchoff, J. F., & Falasca, M. (2019). The impact of buyer-supplier relationship quality and information management on industrial vending machine benefits in the healthcare industry. *Journal of Purchasing and Supply Management*, *25*(3), 100506. https://doi.org/10.1016/j.pursup.2018.06.005

Kumar, P., & Chakraborty, S. (2022). Green service production and environmental performance in healthcare emergencies: role of big-data management and green HRM practices. *The International Journal of Logistics Management*, *33*(4), 1524-1548. https://doi.org/10.1108/IJLM-02-2021-0075

Kuruvilla, J. M., Kathrine, G. J. W., Prasad, G. P., & Evangelina, G. (2023). Implementation of industry 4.0 in supply chain management in the healthcare industry. 2023 2nd International Conference on Edge Computing and Applications (ICECAA), https://doi.org/10.1109/ICECAA58104.2023.10212417

Li, J., & Carayon, P. (2021). Health Care 4.0: A vision for smart and connected health care. *IISE transactions on healthcare systems engineering*, *11*(3), 171-180. https://doi.org/10.1080/24725579.2021.1884627

Liu, L., Song, W., & Liu, Y. (2023). Leveraging digital capabilities toward a circular economy: Reinforcing sustainable supply chain management with Industry 4.0 technologies. *Computers & Industrial Engineering*, *178*, 109113. https://doi.org/10.1016/j.cie.2023.109113

Lodhi, R. N., Asif, M., Abdikarimova, A., & Shahzad, M. F. (2024). Impact of innovation and sustainability on green entrepreneurship: a bibliometric exploration. *Environment, Development and Sustainability*, 1-26. https://doi.org/10.1007/s10668-024-05053-y

Maria Aslam, H., & Siddiqui, D. A. (2023). The Era of Industry 4.0 Technologies and Sustainable Organizational Performance of Pakistan's Garment Industry: The Role of Lean Manufacturing and Green Supply Chain Management Practices with the Moderating Effect of Sustainability Culture. *Danish Ahmed, The Era of Industry*, *4*. https://doi.org/10.2139/ssrn.4431689

Meiling, L., Yahya, F., Waqas, M., Shaohua, Z., Ali, S. A., & Hania, A. (2021). Boosting sustainability in healthcare sector through Fintech: analyzing the moderating role of financial and ICT development. *INQUIRY: The Journal of Health Care Organization, Provision, and Financing*, *58*, 00469580211028174. https://doi.org/10.1177/00469580211028174

Mwanza, J., Telukdarie, A., & Igusa, T. (2023). Impact of industry 4.0 on healthcare systems of low-and middle-income countries: a systematic review. *Health and Technology*, *13*(1), 35-52. https://doi.org/10.1007/s12553-022-00714-2

Paul, S., Riffat, M., Yasir, A., Mahim, M. N., Sharnali, B. Y., Naheen, I. T., Rahman, A., & Kulkarni, A. (2021). Industry 4.0 applications for medical/healthcare services. *Journal of Sensor and Actuator Networks*, *10*(3), 43. https://doi.org/10.3390/jsan10030043

Ramayah, T., Cheah, J., Chuah, F., Ting, H., & Memon, M. A. (2018). Partial least squares structural equation modeling (PLS-SEM) using smartPLS 3.0. *An updated guide and practical guide to statistical analysis*, *1*(1), 1-72. https://www.researchgate.net/profile/Hiram-Ting/publication/341357609

Riaz, A., Rehman, H. M., Sohail, A., & Rehman, M. (2025). Industry 4.0 supply chain nexus: sequential mediating effects of traceability, visibility and resilience on performance. *Asia Pacific Journal of Marketing and Logistics*, *37*(4), 842-860. https://doi.org/10.1108/APJML-02-2024-0202

Saha, P., Talapatra, S., Belal, H., & Jackson, V. (2022). Unleashing the potential of the TQM and industry 4.0 to achieve sustainability performance in the context of a developing country. *Global Journal of Flexible Systems Management*, *23*(4), 495-513. https://doi.org/10.1007/s40171-022-00316-x

Scavarda, A., Daú, G. L., Scavarda, L. F., & Korzenowski, A. L. (2019). A proposed healthcare supply chain management framework in the emerging economies with the sustainable lenses: The theory, the practice, and the policy. *Resources, Conservation and Recycling*, *141*, 418-430. https://doi.org/10.1016/j.resconrec.2018.10.027

Schleper, M. C., Gold, S., Trautrims, A., & Baldock, D. (2021). Pandemic-induced knowledge gaps in operations and supply chain management: COVID-19's impacts on retailing. *International Journal of Operations & Production Management*, *41*(3), 193-205. https://doi.org/10.1108/IJOPM-12-2020-0837

Sibanda, K., Ndayizigamiye, P., & Twinomurinzi, H. (2022). Nindustry 4.0 technologies in maternal healthcare: A systematic review. *IFAC-PapersOnLine*, *55*(10), 2407-2412. https://doi.org/10.1016/j.ifacol.2022.10.069

Söderholm, P. (2013). The political economy of a global ban on mercury-added products: positive versus negative list approaches. *Journal of cleaner production*, *53*, 287-296. https://doi.org/10.1016/j.jclepro.2013.04.019

Sony, M. (2019). Green supply chain management practices and digital technology: A qualitative study. In *Technology optimization and change management for successful digital supply chains* (pp. 233-254). IGI Global. https://doi.org/10.4018/978-1-5225-7700-3.ch012

Swarnakar, V., Bagherian, A., & Singh, A. (2023). Prioritization of critical success factors for sustainable Lean Six Sigma implementation in Indian healthcare organizations using best-worst-method. *The TQM Journal*, *35*(3), 630-653. https://doi.org/10.1108/TQM-07-2021-0199

Thind, P. S., Sareen, A., Singh, D. D., Singh, S., & John, S. (2021). Compromising situation of India's bio-medical waste incineration units during pandemic outbreak of COVID-19: Associated environmental-health impacts and mitigation measures. *Environmental Pollution*, *276*, 116621. https://doi.org/10.1016/j.envpol.2021.116621

Tortorella, G. L., Prashar, A., Antony, J., Fogliatto, F. S., Gonzalez, V., & Godinho Filho, M. (2024). Industry 4.0 adoption for healthcare supply chain performance during COVID-19 pandemic in Brazil and India: the mediating role of resilience abilities development. *Operations Management Research*, *17*(2), 389-405. https://doi.org/10.1007/s12063-023-00366-z

Treacy, R., Humphreys, P., McIvor, R., & Lo, C. (2019). ISO14001 certification and operating performance: A practice-based view. *International journal of production economics*, *208*, 319-328. https://doi.org/10.1016/j.ijpe.2018.12.012

Vishwakarma, A., Dangayach, G., Meena, M., Gupta, S., & Luthra, S. (2023). Adoption of blockchain technology enabled healthcare sustainable supply chain to improve healthcare supply chain performance. *Management of Environmental Quality: An International Journal*, *34*(4), 1111-1128. https://doi.org/10.1108/MEQ-02-2022-0025

Wang, C., Zhang, Q., & Zhang, W. (2020). Corporate social responsibility, Green supply chain management and firm performance: The moderating role of big-data analytics capability. *Research in Transportation Business & Management*, *37*, 100557. https://doi.org/10.1016/j.rtbm.2020.100557

Wu, F., Yeniyurt, S., Kim, D., & Cavusgil, S. T. (2006). The impact of information technology on supply chain capabilities and firm performance: A resource-based view. *Industrial Marketing Management*, *35*(4), 493-504. https://doi.org/10.1016/j.indmarman.2005.05.003

Yildiz Çankaya, S., & Sezen, B. (2019). Effects of green supply chain management practices on sustainability performance. *Journal of Manufacturing Technology Management*, *30*(1), 98-121. https://doi.org/10.1108/JMTM-03-2018-0099

Ziyadeh, M. W., Othman, M., & Zaid, A. A. (2023). Effects of green human resource management on organisational sustainability: the mediating role of corporate social responsibility and organisational citizenship behaviour. *International Journal of Organizational Analysis*, *32*(2), 357-372. https://doi.org/10.1108/IJOA-11-2022-3506