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Industry 4.0 Technology Adoption and Sustainable Business Performance: The Mediating Role of Green Supply Chain Management and the Moderating Effects of Sustainability Awareness

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Abstract

The growing adoption of Industry 4.0 technologies has transformed organizational processes, yet the mechanisms through which digital transformation enhances sustainable business performance remain unclear, especially in emerging economies. Drawing on the Resource-Based View, Natural Resource-Based View, Dynamic Capabilities Theory, and Upper Echelons Theory, this study examines the impact of Industry 4.0 technology adoption on Sustainable Business Performance (SBP), emphasizing the mediating role of Green Supply Chain Management (GSCM) and the moderating effect of Sustainability Awareness (SA). Using survey data from 355 manufacturing firms in Pakistan, India, and Bangladesh, the study applies Partial Least Squares Structural Equation Modeling (PLS-SEM) to test a moderated mediation framework. The results indicate that Industry 4.0 adoption significantly improves both GSCM and sustainable business performance. GSCM serves as a strong mediator, suggesting that digital technologies contribute to sustainability primarily by strengthening green supply chain practices. Moreover, Sustainability Awareness enhances the effects of Industry 4.0 adoption on GSCM, strengthens the influence of GSCM on sustainable performance, and amplifies the overall indirect impact of digital adoption on sustainability outcomes. These findings demonstrate that technological capabilities generate sustainable value most effectively when embedded in green operational processes and guided by sustainability-oriented managerial cognition. This study contributes to the digital sustainability and supply chain literature by offering a process-based, context-sensitive explanation of how Industry 4.0 fosters sustainable business performance, providing practical insights for managers and policymakers seeking to align digital transformation with long-term environmental, social, and economic goals.

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Keywords: Industry 4.0 Technology Adoption; Green Supply Chain Management; Sustainable Business Performance; Sustainability Awareness; Digital Transformation; Moderated Mediation; Emerging Economies; PLS-SEM.

INTRODUCTION

The rapid proliferation of Industry 4.0 technologies has fundamentally transformed how companies plan, manage, and optimize supply chain and operational processes. The most advanced digital technology, such as the Internet of Things (IoT), analytics on big data, artificial intelligence (AI), blockchain, and cyber-physical systems, facilitates real-time data exchange, predictive decision-making, and visibility of the entire supply chain, thereby altering the classic production and logistics models (Elaaguir& Al Meriouh, 2024; Al-Okaily et al., 2024). In addition to efficiency and cost-cutting, Industry 4.0 is also positioned as a strategic driver of sustainability, enabling

organizations to integrate environmental and social goals into their primary business operations. Sustainable business performance, the ability to simultaneously satisfy the environmental stewardship, social responsibility, and economic viability, has become a paramount issue in firms in intensely competitive and stakeholder-oriented business settings. Tighter regulations, expanded audits of the worldwide supply chain, and lower investor expectations now require organizations to report evidence-based sustainability performance rather than mere compliance. Nevertheless, new trends indicate that digital adoption is not necessarily a guarantee of sustainable performance. Rather, the sustainability contribution of Industry 4.0 relies primarily on the location of the digital capabilities within organizational processes and managerial practices (Elaaguir vs. Elaaguir& Al Meriouh, 2024; Al-Okaily et al., 2024).

In this context, Green Supply Chain Management (GSCM) has been identified as one of the central organizational processes in which digital technologies can be formalized towards sustainability outcomes. GSCM integrates environmental considerations into procurement, production, logistics, and reverse flows, enabling firms to operate efficiently and responsibly toward the environment. Recent research demonstrates that Industry 4.0 technologies complement GSCM by enabling supplier tracing and monitoring, eco-design, and waste minimization,thereby positively affecting the environment and the economy. Despite these revelations, the mediating role of GSCM is both theoretically incomplete and empirically disjointed, particularly in the literature, where sustainability outcomes are perceived as direct implications of technology adoption.

In addition, the efficacy of Industry 4.0 and GSCM practices is likely to vary across organizations. The level of sustainability awareness, as a concept that can be defined as the degree to which firms seek sustainability as a strategic priority but not as a compliance cost can have a pivotal influence on the implementation and utilization of digital technologies. High sustainability awareness is more likely to lead organizations focus Industry 4.0 investments on long-term environmental and social value generation, instead of operational benefits in the short term (Al-Okaily et al., 2024). Recent studies continue to stress the fact that managerial cognition, sustainability orientation, and organizational culture are boundary conditions that can make or break the digital transformation in terms of sustainable outcomes (Elaaguir vs. Elaaguir& Al Meriouh, 2024). Nevertheless, low sustainability awareness has rarely been investigated as a moderating variable in the integrated digital sustainability models.Although the topic is becoming increasingly popular among scholars, current literature continues to focus on Industry 4.0 adoption, GSCM, and sustainable performance separately or presumes that these concepts are directly and linearly related to one another. That creates a gaping void as to how and on what terms digital technologies sustain business performance. The discrepancy is especially acute in the context of emergingeconomies,

where the institutional weakness, resourcescarcity,and disproportionate sustainability commitments can enhance the significance of the organizational mechanisms and the managerial consciousness .To close these gaps, this paper constructs and empirically validates a synthesized framework that considers Green Supply Chain Management as a centralizing process by through which Industry 4.0 technology adoption is associated with sustainable business performance, and studies sustainability awareness as a moderating boundary condition.

The proposed model has been developed and is based on the Resource-Based View and the Dynamic Capabilities Theory, viewing Industry 4.0 technologies as strategic

resources whose sustainability value can be achieved only when they are implemented with the support of green supply chain capabilities, which in turn are supported by sustainability-related managerial cognition. In this way, the present study will contribute to the literature on digital sustainability and supply chain by clarifying not only whether Industry 4.0 enhances sustainable performance, but also how and under what conditions organizations achieve this enhancement.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Industry 4.0 Technology Adoption as a Strategic Digital Capability

Industry 4.0 (I4.0) is a radical transformation of industrial systems that incorporates high-tech digital technologies, such as the Internet of Things (IoT), big data analytics, artificial intelligence (AI), cyber-physical systems, and intelligent automation. These technologies facilitate the visibility of real-time data, predictive analytics, and decentralized decision-making across organizational and supply chain boundaries, thereby transforming how companies create and capture value (Frank et al., 2019; Sony and Naik, 2020; Muller et al., 2023).

Based on the Resource-Based View (RBV), I4.0 technologies can no longer be viewed and understood as solitary tools but as strategic digital capabilities, the value of which is determined by how firms can integrate, remake, and realize in ways specific to a firm (Barney, 1991; Teece, 2018). Although the spread of digital technologies has decreased their exclusivity, the sustainable advantage is increasingly based on the interdependent organizational processes that create the accompanying space of routine, architectural processes of decision-making, and mechanisms of coordination between firms (Dalenogare et al., 2023; Tortorella et al., 2024).

Existing empirical studies associate I4.0 implementation with enhanced energy consumption, waste management, operational flexibility, and environmental surveillance, which are some fundamental aspects of sustainable business performance (Bag et al., 2021; Khan et al., 2024). Digitalization helps companies to be economically efficient and environmentally responsible at the same time, which in turn helps them achieve the triple bottom line of sustainability (Elkington, 1997). Nevertheless, recent research warns against technological determinism, which states that the advantages of sustainability following the adoption of I4.0 are disproportionate, delayed, or dependent on the organizational setting (Bai et al., 2022; Ghobakhloo et al., 2024).

In fact, new evidence that I4.0 implementation disciplines are not enough to produce sustainable results unless digital capabilities are reconfigured into ecologically friendly practices. This poses important questions as to how and in what circumstances digital adoption may a part of sustainable business performance. In line with this, it is postulated that there will be a positive relationship between the baseline and that the relationship will tend to be indirect and dependent on the mechanisms.

H1: Industry 4.0 technology adoption positively influences sustainable business performance.

Green Supply Chain Management as a Value-Conversion Mechanism

Green Supply Chain Management (GSCM) is defined as the logical approach to incorporating environmental concerns into the supply chain operations, such as green purchasing, eco-design, cleaner production, and reverse logistics (Zhu et al.,

2008). Building on the RBV, the Natural Resource-Based View (NRBV), the authors claim that firms attain sustainable competitive advantage through the development of capabilities, which minimize environmental harm and maximize efficiency and legitimacy at the same time (Hart, 1995; Hart and Dowell, 2011).

Industry 4.0 technologies are key enablers of GSCM that improve the level of transparency, traceability, and coordination within complex supply networks. Indicatively, IoT-based sensors are used to monitor the environment in real-time, blockchain technologies are used to improve transparency of the green sourcing, and sophisticated analytics are used to optimize emissions and minimize waste (Kouhizadeh et al., 2022; Gupta et al., 2024). These mechanisms convert the digital capabilities into ecologically responsible supply chain practices rather than treating them as abstract technological possessions.

GSCM is especially relevant in comparison with other organizational mechanisms, i.e., operational excellence or green innovation all due to the fact that it directly inserts the environmental intent into inter-organizational environment, in which a considerable part of the environmental impacts takes place. With this, GSCM serves as a mechanism for value conversion, a process that convert digital potential into quantifiable sustainability outputs. Empirical research is starting to show that companies that align I4.0 implementation with GSCM practices have better environmental and operational performance, especially in globally dispersed and resource-constrained environments (Bag et al., 2021; Ghobakhloo et al., 2023). The meta-analytical evidence also shows that GSCM is one of the key channels by which technological capabilities affect sustainability (Bai et al., 2022; Li et al., 2024). However, the outcomes of the implementing of GSCM differ actoss companies, and it may be assumed that digital implementation can improve sustainability most of the time when it is incorporated in consistent green supply chain policies.

H2: Industry 4.0 technology adoption positively influences green supply chain management practices.

H3: Green supply chain management positively influences sustainable business performance.

H4: Green supply chain management mediates the relationship between Industry 4.0 technology adoption and sustainable business performance**.**

Sustainability Awareness as a Contextual Boundary Condition

Though green supply chain practices and digital technologies offer the structural and working capabilities, the efficiency of their application is essential to managerial cognition and organizational values. The awareness of sustainability demonstrates that organizational decision-makers are aware, value and internalize the environmental and social responsibilities in making strategic decisions (Roxas and Coetzer, 2012). The concept illustrations of sustainability awareness are at the organizational level in this study in terms of collective managerial orientations as well as strategic priorities.

Using the Upper Echelons Theory, managerial beliefs and frames of cognition influence the meaning and understanding of organizational resources, their dispersion, and the manner in which they are adjusted and aligned to the long-term goals (Hambrick and Mason, 1984). The sustainability awareness gets especially consequential in digitally intensive settings since Industry 4.0 technologies, in turn, are

both flexible and value-neutral, which means that their usage in the context of sustainability objectives has to be influenced by managerial intent as opposed to technical ability (Rehman et al., 2023; Wang et al., 2024).

Companies that have a high level of sustainability consciousness tend to use GSCM practices in a proactive way, focusing on the creation ofenvironmental and social rather than cosmetic compliance or immediate efficiency.

Companies with a high level of sustainability consciousness tend to use GSCM practices in a proactive way, where they focus on the creation of long-term environmental and social values instead of cosmetic compliance or immediate efficiency. According to the recent studies, sustainability-related managerial thinking reinforces the performance effects of green practices by promoting stakeholder connections, cross-functional alignment, and environmental enhancement (Zhang et al., 2022; Abbas and Sağsan, 2024).

On this note, sustainability awareness does not necessarily result in sustainability but rather it operates as a contextual condition, which is a boundary condition that enhances the efficacy of green supply chain practices.

H5: Sustainability awareness positively moderates the relationship between green supply chain management and sustainable business performance, such that the relationship is stronger when sustainability awareness is high.

Moderating Role of Sustainability Awareness in Industry 4.0 Adoption

The Industry 4.0 technologies have a high potential of enhancing environmental efficiency, social responsibility, and economically sustainable but such level of performance depends on the deployment performance of the firms. IoT, artificial intelligence, and big data are digital tools that are value-neutral and demand managerial guidance to deliver the sustainability results (Ghobakhloo et al., 2023; Tortorella et al., 2024). As stated in the Upper Echelons Theory, the utilisation of technological resources is influenced by managerial cognition and sustainability-oriented leadership. Companies that are more sustainability conscious are also more likely to coordinate Industry 4.0 adoption with long-term environmental and social objectives, which would reinforce sustainable business performance (Hambrick and Mason, 1984; Wang et al., 2024). The most recent literature proves that sustainability-focused approaches to managerial thinking enhance the sustainability of digital transformation (Rehman et al., 2023; Al-Okaily et al., 2024).

H6: Sustainability awareness positively moderates the relationship between Industry 4.0 technology adoption and green supply chain management, such that the relationship is stronger when sustainability awareness is high.

Moderated Mediation Role of Sustainability Awareness in Industry 4.0 Sustainability Outcomes

The primary ways that industry 4.0 technologies contribute to sustainable business performance are indirect business processes, especially green operational business models and supply chain models. IoT, AI, and big data analytics can only be used to maximize resource efficiency and enhance traceability and environmental impact, although these benefits are most sustainable when implemented as part of the systemic green supply chain management (GSCM) (Bag et al., 2021; Kumar et al., 2023; Yadav et al., 2024). This points out GSCM as one of the key mediating pathways within which Industry 4.0 is converted into sustainability results.

Green Supply Chain Management is a key component of transforming technological opportunities into environmental and economic results, and contributing to cleaner production, responsible sourcing and sustainable logistics (Zhu et al., 2020; Awan et al., 2023). It is empirically proven that companies using both digital technologies and green supply chain management attain greater sustainability and competitive advantages as compared to companies using technologies exclusively (Khan et al., 2022; Lin et al., 2024).

The performance of this mediated relationship is, however, depends on organizational sustainability awareness that mirrors managerial commitment, environmental values and strategic orientation towards sustainable development. Sustainability awareness also enhances the capacity of firms to use Industry 4.0 technologies to transform into a green entity by informing investment priorities, operational behaviors in line with sustainability objectives, and accountability systems (Hussain et al., 2021; Shahzad et al., 2023; Ullah et al., 2024). The high level of sustainability awareness in firms is more likely to lead to the integration of digital innovations into the proactive GSCM strategies and thus increase the indirect impact on sustainable business performance.

Based on the Natural Resource-Based View (NRBV) and Dynamic Capabilities Theory, sustainability awareness serves as a strategic thinking resource that increases the ability of firms to convert technological capabilities into sustainable value by using the concept of green supply chains (Hart and Dowell, 2011; Teece, 2020; Li et al., 2023). As a result, it is anticipated that the mediated relationship between Industry 4.0 adoption and sustainable business performance through GSCM will be positive, because it is driven by sustainability awareness.

Hypothesis 7: Sustainability awareness positively moderates the indirect relationship between Industry 4.0 technology adoption and sustainable business performance through green supply chain management, such that the mediated effect is stronger when sustainability awareness is high

Integrated Theoretical Model

Combining the Resource-Based View, the Natural Resource-Based View, and the Upper Echelons Theory, the given model will conceptualize the adoption of Industry 4.0 technology as a strategic digital capability where the sustainability value is achieved through the organization processes and managerial cognition. RBV and NRBV describe the transformation of firm-specific digital capabilities and how this conversion is turned into environmental and economic value produced through green supply chain management, and Upper Echelons Theory explains the variability of findings due to the presence of sustainability awareness as a contextual boundary condition.

This framework sheds light on Industry 4.0, as a contingent, by shifting the emphasis from linear stories of technology and technology-centric accounts of sustainability, to contingent capabilities based on how digital resources are operationalized and cognitively represented in the organizational context. This way, the absence of previous studies focused on more process-centered and context-sensitive process models of Industry 4.0 enabled sustainability and known how and why digital transformation is relevant to sustainable business performance (Tortorella et al., 2024; Ghobakhloo et al., 2025). The proposed model was shown in figure 01.

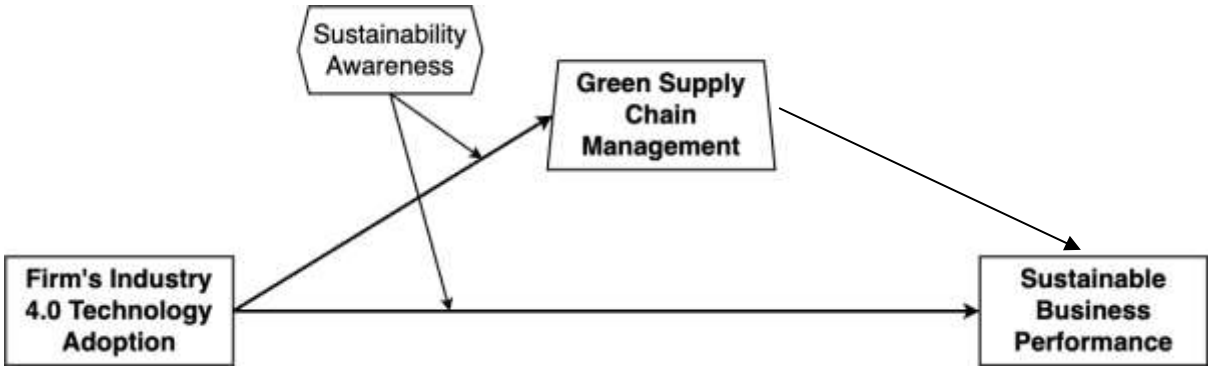

Figure 1.
Conceptual framework of the study

Research Methodology

This study utilizes quantitative method, and a sample frame derived from datasets of regional statistical agencies, chambers of commerce, and economic ministries across South Asia, including Pakistan bureau of statistics, the Bureau of Statistics, India's Ministry of Statistics and Program Implementation, Bangladesh Bureau of Statistics, Sri Lanka's Department of Census and Statistics, and other relevant business directories or industry associations in top South Asian countries. The sample size determined based on the formula considering the desired confidence level (95%), the margin of error (5%), and an estimated population variance i.e. 384.

Measurement of Variables

The Constructs were measurement through validated scales developed by adapting previous studies with slight modification of words in the text to achieve contextual relevance in Pakistan, India and Bangladesh without distorting the conceptual meanings.

The adoption of Industry 4.0 technology was measured on a 10-item scale whose statements were based on Bag et al. (2021) and referred to the adoption of core digital technologies, including IoT, big data analytics, automation, and smart manufacturing systems, within the last three years. There was a 5-point Likert scale rating items (1 = strongly disagree, and 5 strongly agree).

Green Supply Chain Management (GSCM) was conceptualized as a multidimensional concept that is measured using 21 items that include internal environmental management, green purchasing, customer cooperation, and eco-design, based on the adaptations of Fang and Zhang (2018) and Reefke and Sundaram (2018). The responses had to be stated on a 5-point Likert scale as the practices of green supply chains are process based and inter-organizational.

The measurement of sustainable business performance (SBP) was done as a triple bottom line construct of economic, environmental and social performance. Fifteen (15) items (one per dimension) were taken from existing literature (Paulraj et al., 2014; Kumar et al., 2018; Crick, 2021; Kallmuenzer et al., 2021; Mwesiumo et al., 2023) and measured in a 5-point Likert scale.

The sustainability awareness (SAW) was assessed by a single item measure that comprehended the general awareness of the firm concerning the sustainability issues in its supply chain operations. This methodology is suitable to concrete and one-dimensional constructs and has previous measurement empirical studies as its backing (Bergkvist and Rossiter, 2009; Bergkvist, 2015, 2016), especially in survey research at the firm level, with top-level managers.

RESULT

Table 1 results suggest that the measurement model can be used in accordance with the accepted psychometric norms. The majority of the indicator loadings are greater than the recommended indicator reliability of 0.70, which indicates a high level of indicator reliability, and only some indicators between 0.50 and 0.69 (e.g., ATA3, GSCM4, GSCM8, SBP10) are acceptable as they possess sufficient construct reliability and content validity (Hair et al., 2019). The Alpha value of Cronbach (0.860-0.893) and Composite Reliability value (0.883-0.913) are above the anticipated 0.70, which represents high internal consistency of the scale items (Nunnally, 1994). The AVE values (0.521- 0.523) exceed the required level of 0.50, showing that each construct explains more than half of the variance in its indicators and therefore, is sufficiently convergent (Fornell and Larcker, 1981). The values of Variance Inflation Factor (VIF) are less than the critical value of 5.0 (more are less than 3.3). Therefore, the results indicates that there are no severe issues of multicollinearity among the indicators (Kock, 2015; Hair et al., 2019). Sustainability Awareness is assessed with the help of a single-item measure, which is acceptable provided that the construct is well-defined, though multi-item scales are usually the more desirable in the case of higher reliability (Diamantopoulos et al., 2012). All in all, the results indicate that the measurement model has good reliability, convergent validity, and collinearity diagnostics, which indicates that it presents the most appropriate model in the structural model analysis.

Table 1.
Reliability, validity and collinearity (VIF)

Item	Loading	VIF	Alpha	CR	AVE
Industry 4.0 Technology Adoption					
ATA1	0.735	2.131	0.860	0.888	0.521
ATA2	0.742	2.039			
ATA3	0.604	1.530			
ATA4	0.712	2.017			
ATA5	0.732	2.575			
ATA6	0.700	2.939			
ATA7	0.744	2.306			
ATA8	0.732	2.409			
ATA9	0.723	3.231			
ATA10	0.700	3.151			
Green Supply Chain Management					
GSCM1	0.768	3.514	**0.893**	**0.913**	**0.523**

GSCM2	0.802	3.121			
GSCM3	0.722	3.227			
GSCM4	0.638	2.671			
GSCM5	0.775	2.591			
GSCM6	0.713	2.960			
GSCM7	0.694	3.883			
GSCM8	0.654	2.320			
GSCM9	0.724	3.724			
GSCM10	0.739	2.857			
GSCM11	0.757	3.231			
GSCM12	0.759	2.818			
GSCM13	0.709	2.201			
GSCM14	0.660	2.581			
GSCM15	0.783	2.175			
GSCM16	0.753	2.692			
GSCM17	0.796	2.037			
GSCM18	0.732	2.993			
GSCM19	0.812	3.235			
GSCM20	0.738	3.595			
GSCM21	0.731	3.236			
Sustainability Awareness					
SA1	1.000	1.000			
Sustainable Business Performance					
SBP1	0.868	2.175	**0.863**	**0.883**	**0.522**
SBP2	0.869	2.342			
SBP3	0.712	2.134			
SBP4	0.823	2.342			
SBP5	0.832	3.234			
SBP6	0.732	2.424			
SBP7	0.724	2.524			
SBP8	0.707	2.342			
SBP9	0.794	2.324			
SBP10	0.679	2.034			
SBP11	0.778	2.994			
SBP12	0.885	3.234			
SBP13	0.723	3.342			
SBP14	0.827	2.443			
SBP15	0.724	3.244			
SA x Alt					1.000

Table 2 indicates discriminant validity based on the Heterotrait-monomethod Ratio (HTMT). All the values of HTMT values are below than the recommended value of 0.85, which means that the constructs are empirically different and measure distinct theoretical concepts. The largest value (GSCM -SBP = 0.810) is within acceptable ranges, which proves that there is no important intertwining of constructs. In general, the findings indicate sufficient discriminant validity and indicate the strength of the measurement model (Henseler et al., 2015). Table 3 shows the discriminant validity through FornellLarcker criterion where the square root of AVE (diagonal elements) should be greater than inter-construct correlations. The findings suggest that the values of Alt (0.722), GSCM (0.723), SA (1.000), and SBP (0.722) are higher than their corresponding correlation coefficients, thus the presence of satisfactory discriminant validity. GSCM and SBP (0.453) have a close correlation, which is significantly lower

than the diagonal values and it indicates that the constructs are conceptually different but they are correlated (Fornell and Larcker, 1981).

Table -2
Heterotrait–Monotrait Ratio

	Alt	GSCM	SA	SBP	SA x Alt
Alt					
GSCM	0.559				
SA	0.700	0.567			
SBP	0.515	0.810	0.572		
SA x Alt	0.421	0.316	0.282	0.316	

Table-3.
Fornell Larcker

Variables	Alt	GSCM	SA	SBP
Alt	0.722			
GSCM	0.526	0.723		
SA	0.662	0.571	1.000	
SBP	0.481	0.453	0.565	0.722

4.2STRUCTURE MODEL

Main Results of the Structural Model Table

The findings reveal that all the conceptualized relationships are positive, statistically significant and empirically supported, which proves the strength of the postulated framework.The positive impact on the Green Supply Chain Management (GSCM) (β = 0.237, p = 0.009) and Sustainable Business Performance (SBP) (β = 0.617, p < 0.001) is significant, and industry 4.0 Adoption (Alt) positively influences the adoption of digital technology to improve green practices and green outcomes of the supply chain. Green Supply Chain Management has a strong positive effect on Sustainable Business Performance (0.733, p < 0.001), which has been the key to the environmental, social, and economic performance.

The mediation analysis indicates that GSCM is a significant mediator of the Industry 4.0 Adoption effect on Sustainable Business Performance (0.173, p = 0.007) which implies that a portion of the sustainability value of digital adoption is transmitted through Improved green supply chain practices. The findings indicate that moderating effect of Industry 4.0 Adoption on GSCM (= 0.290, p < 0.001). Whereas, the effect of GSCM on SBP (= 0.110, p = 0.045) is significant in the presence of Sustainability Awareness (SA). Lastly, the moderated mediation effect is high (0.066, p < 0.001), showing that Sustainability Awareness enhances the indirect effect of Industry 4.0 Adoption on Sustainable Business Performance by Green Supply Chain Management.

Hypothesis Structural Path
Table 4

Hypothesis	Beta	Standard Deviation	T-value	P-value	Decisions
Industry 4.0 Adoption (Alt) → Green Supply Chain Management (GSCM)	0.237	0.085	2.611	0.009	**Supported**
Industry 4.0 Adoption (Alt) → Sustainable Business Performance (SBP)	0.617	**0.253**	**2.431**	**0.000**	**Supported**
Green Supply Chain Management (GSCM) → Sustainable Business Performance (SBP	0.733	0.043	17.274	0.000	**Supported**

AIt → GSCM → SBP (Indirect/Mediating Effect)	0.173	0.060	2.707	0.007	**Supported**
Sustainability Awareness (SA) × AIt → GSCM (Moderation)	0.290	0.099	2.920	0.000	**Supported**
Sustainability Awareness (SA) × GSCM → SBP (Moderation)	0.110	0.056	2.007	0.045	**Supported**
SA × (AIt → GSCM → SBP) (Moderated Mediation)	0.066	0.027	2.444	0.000	**Supported**

5-DISCUSSION

The findings provide strong empirical evidence for the suggested model that industry 4.0 implementation increases sustainable business performance both directly and indirectly through Green Supply Chain Management. Moreover, these results align with the Resource-Based View (RBV) and Dynamic Capabilities Theory. The positive influence of Industry 4.0 Adoption on GSCM (0.237 p = 0.009) is significant, suggesting that digital technologies are strategic organizational resources that enhance the capacity of firms to engage in environmentally responsible supply chain practices. This is consistent with RBV that posits competitive advantage is manifested in the effective implementation of valuable and hard-to-copy technological capabilities by the firms (Barney, 1991; Teece, 2018). The outcome confirms earlier data regarding the benefits of IoT, AI, and data analytics to enhance supply chains' traceability, efficiency, and environmental monitoring (Bag et al., 2021; Kouhizadeh et al., 2022; Gupta et al., 2024).

Industry 4.0 Adoption exerting a strong influence on Sustainable Business Performance (= 0.617, p < 0.001) supports the fact that digital transformation leads to better environmental, economic, and social performance, which is another argument in favor of the view of the triple bottom line (Elkington, 1997). This result is congruent with the literature that illustrates that Industry 4.0 improves energy efficiency, waste reduction, and operational flexibility (Khan et al., 2024; Muller et al., 2023). Regarding Dynamic Capabilities perspective, the outcomes of the study reveal that the ability of firms to reorganize the use of technology resources is associated with the long-term benefits in performance in the rapidly changing environment (Teece, 2018; Tortorella et al., 2024).

The positive impact of Green Supply Chain Management on Sustainable Business Performance is very strong (= 0.733, p = 0.001), which validates the fact that GSCM is a very important value conversion mechanism. This is in line with the Natural Resource-Based View (NRBV), which argues that sustainable competitive advantage in firms is attained through the development of capabilities that minimize environmental degradation and increase efficiencies and legitimacy (Hart, 1995; Hart and Dowell, 2011). The finding is in line with previous studies that demonstrated that green purchasing, eco-design, reverse logistics, and cleaner production show a significant increase in sustainability outcomes (Zhu et al., 2008; Awan et al., 2023; Lin et al., 2024).

The mediation effect (AIt to GSCM to SBP; 0.173, 0.007) shows that the Industry 4.0 technologies create sustainability value, but not due to technology per se, but through its operational connectivity into the green supply chain practices. This along with some recent arguments that digital technologies are facilitators and not intrinsic drivers of sustainability and that they have an effect that is determined by implementation at the processes level, (Bai et al., 2022; Ghobakhloo et al., 2024). The

observation supports the theoretical stance that organizational operations convert the technological potential into physical sustainability performance.

The results of the moderation give a good support of the application of Sustainability Awareness as a contextual constraint condition, which is in line with the Upper Echelons Theory. The great association between Sustainability Awareness and Industry 4.0 Adoption on GSCM (0.290, $p < 0.001$) reveals that managerial cognition and sustainability-based values enhance the capability of firms to convert digital investments to green supply chain services. This is consistent with the argument of Hambrick and Mason (1984) that executive beliefs are the determinant of strategic decisions and the recent results that sustainability-focused leadership increases the success of digital transformation (Rehman et al., 2023; Wang et al., 2024).

Equally, the Sustainability Awareness moderating role in the GSCM 0 SBP relationship (0.11045) implies the green supply chain practices have greater sustainability performance when the strategic commitment of firms to sustainability is higher. It is consistent with the literature that emphasizes the idea that sustainability minded managerial thinking positively affects the performance impact of green practices by increasing stakeholder congruence, cross-functional coordination and long-term environmental commitment (Zhang et al., 2022; Abbas and Sağsan, 2024).

Above all, the fact that Sustainability Awareness has a significant moderated mediation effect (= 0.066, $p < 0.001$) indicates that the indirect effect of Industry 4.0 Adoption on Sustainable Business Performance mediated through Green Supply Chain Management is significant. This finding is a combination of RBV, NRBV, Dynamic Capabilities Theory, and Upper Echelons Theory, showing that technological resources can generate sustainable value only when they are engrained in green operational capabilities and with the help of sustainability-oriented managerial cognition (Hart and Dowell, 2011; Teece, 2020; Li et al., 2023).

All in all, the results contribute to the current theory by demonstrating that Industry 4.0 implementation is not enough to guarantee sustainable performance. Rather, the process-based approach leads to sustainability outcomes, which are operationalized in terms of GSCM and reinforced by the sustainability awareness at the managerial tier. This builds on more recent literature by providing a process-oriented and contextual account of how and in what conditions digital transformation contributes to sustainable business performance.Thus the emerging economies, where institutional and resource factors increase the relevance of internal competencies and leadership orientation.

Theoretical Implications

There are several valuable theoretical contributions of this research to the sustainability, digital transformation literature, and supply chain management. To begin with, it builds on the Resource-Based View (RBV) and Natural Resource-Based View (NRBV) to empirically confirm that Industry 4.0 technologies can serve as a strategic digital resource and as enablers of operationally and environmentally oriented capabilities. The results affirm that technological resources in themselves are not necessarily associated with sustainable performance; instead, their impact is achieved when they are incorporated in the practices of Green Supply Chain Management (GSCM) that transform digital potential into environmental and economic performance.

Second, the research advances the Dynamic Capabilities Theory by demonstrating that companies should continuously reorganize both technological and environmental capabilities to attain sustainable business performance. The high level of mediating influence of GSCM is an empirical observation that benefits of sustainability are attained not by the direct impact of technology but by the coordination of capabilities.

Third, the presence of Sustainability Awareness as a moderator allows the research to add to Upper Echelons Theory, focusing on the critical status of managerial cognition, values, and decision-making based on sustainability and its impact on the implementation of digital and green capabilities. This confirms that the sustainability results are neither technological nor operational phenomena, but they are strongly dependent on the mindset of leadership, as well as on the organizational orientation.

Lastly, the analysis contributes to the growing body of knowledge on moderated mediation in sustainability studies, because it proves that sustainability awareness enhances both the direct and indirect relationships between Industry 4.0 adoption and sustainable business performance. This offers a more process-based and context-sensitive meaning of how digital transformation can result in sustainability and solves an important gap in previous studies that considered technology-performance relationships as linear and universal.

MANAGERIAL IMPLICATIONS

The results offer several useful lessons for managers, policymakers, and business executives interested in using digital transformation to achieve sustainability.

To start with, managers need to understand that adopting Industry 4.0 alone is not enough to achieve sustainable performance. Companies are advised to make use of digital technologies in the green supply chain system (green procurement, green design, cleaner production, and reverse logistics) in a strategic manner, to be sure that the technological investments are bringing quantifiable sustainability gains.

Second, there should be an active construction of sustainability awareness within the organizations in the leadership and managerial level. Managerial commitment can be reinforced with the help of training programs, sustainability-based leadership development, and internal communication strategy, as well as make sure that the digital transformation initiatives also serve the long-term environmental and social objectives.

Third, Industry 4.0 technologies are to be utilized by firms so that supply chains become more transparent, traceable, and monitored on the environment allowing data-driven decisions that minimise waste, emissions, and inefficiencies in the supply chain. This has the capability of enhancing compliance with regulations, stakeholder confidence and corporate image.

Fourth, the top management would need to incorporate sustainability in the strategic planning, governance and performance measurement systems. Firms can enhance the translation of green initiatives into high-quality business performance by aligning incentives, reporting systems, and operational goals with sustainability goals.

Lastly, policymakers and industry stakeholders need to support organizations with regulatory incentives, the development of digital infrastructure, and sustainability awareness campaigns, especially in emerging economies where resource constraints can hinder the successful implementation of Industry 4.0 technologies.

CONCLUSION

This study examines the empirical relationships among Industry 4.0 technology adoption and Green Supply Chain Management (GSCM), Sustainability Awareness (SA), and Sustainable Business Performance (SBP). These findings support that the adoption of Industry 4.0 has a positive impact on both GSCM and SBP and that GSCM is a significant mediator in this connection. In addition, Sustainability Awareness reinforces the Industry 4.0 impacts on GSCM, the GSCM and Industry 4.0 connections and the greater impact on the indirect relationship between the adoption and sustainability performance. These findings indicate that sustainable business performance is not merely a direct by-product of the adoption of digital technology; instead, they rely on appropriate green operational practices and sustainability-oriented managerial cognition. The research paper is a contribution to the literature because it combines RBV, NRBV, Dynamic Capabilities Theory, and Upper Echelons Theory and offers a process-driven and situation-sensitive argument on how the digital transformation can be used to generate sustainable performance, especially in the context of resource-constrained and emerging markets.

RECOMMENDATIONS

1. Strategic Technology Integration: It is necessary to emphasize that organizations should focus on merging Industry 4.0 technologies with business operations, specifically, GSCM, rather than perceive technology adoption as an independent initiative.

2. Improve Managerial Sustainability Consciousness: Companies are advised to invest in managerial training and leadership development that views sustainability as a strategic focus to ensure that the digital transformation is maximized.

3. Green Operational Practices: The managers ought to reinforce the eco-design, green procurement, cleaner production, and reverse logistics to ensure that technological investments can be transformed into practical environmental and economic gains.

4. Policy and Governance Alignment: To promote legitimacy and trust in the stakeholders, firms are advised to align internal sustainability efforts to national and international regulations and standards, and reporting mechanisms.

5. Long-term Focus: To achieve the maximum potential of Industry 4.0 adoption, decision-makers ought to focus on long-term sustainability benefits, rather than operational efficiency in the short-term.

LIMITATIONS OF THE STUDY

1. Cross-Sectional Design: The study involved cross-sectional data and hence lacks the capability of inferences of causal relationships. The longitudinal designs would enable future studies to have a long-term focus on the sustainability impacts of Industry 4.0 adoption.

2. Geographical Context: The research is based on companies in the emerging economies and this could restrict the extrapolation of the results to the developed markets with a different institutional and resource base.

3. Self-Reported Measures: The primary methods of data collection were the use of surveys, which can cause bias because of subjective views of respondents on the use of technology, GSCM practices, and awareness on sustainability.

4. Sectoral Specificity: The research failed to differentiate the industrial sectors and this may have implications for the generalizability of findings in other sectors that have distinct supply chain features.

5. Moderating Factors: Only Sustainability Awareness was taken as a moderating factor. The variability in sustainable business performance can be further explained by other organizational and environmental moderating factors e.g. organizational culture or regulatory pressure.

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