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INDUSTRY 4.0, KNOWLEDGE MANAGEMENT, SUSTAINABLE PERFORMANCE: THE MEDIATING ROLE OF GREEN SUPPLY CHAIN COLLABORATION

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Abstract
This study examines how Industry 4.0 (I4.0) and Knowledge Management (KM) influence Sustainable Performance (SP) through Green Supply Chain Collaboration (GSCC) in pharmaceutical manufacturing firms. A quantitative survey was conducted among managers of Good Manufacturing Practice certified pharmaceutical manufacturers in the Jabodetabek region of Indonesia. A total of 425 valid responses were analysed using Partial Least Squares Structural Equation Modelling to test the direct and mediating relationships among I4.0, KM, GSCC, and SP. The results show that I4.0 significantly enhances both GSCC and SP, while KM positively influences GSCC but does not have a significant direct effect on SP. GSCC also positively affects SP and mediates the relationship between I4.0 and SP, although the direct effect of I4.0 on SP remains stronger than the mediated pathway. These findings indicate that digital capability plays a more dominant role than knowledge capability in driving sustainable performance in highly regulated pharmaceutical supply chains. For managers, the results highlight the importance of prioritizing digital capability development and strengthening collaborative supply chain mechanisms to achieve sustainability outcomes.

Keywords: Industry 4.0, Knowledge management, Green supply chain collaboration, Sustainable performance, Pharmaceutical industry.
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1. INTRODUCTION

The contemporary manufacturing landscape is increasingly shaped by sustainability pressures arising from climate change, environmental degradation, resource scarcity, and heightened stakeholder scrutiny (Li & Thurasamy, 2025; Mukhtar et al., 2025; Oyelakin et al., 2025). As sustainability indicators become embedded in corporate performance evaluation, firms are compelled to integrate environmental and social considerations into core strategic and operational decisions. Sustainability is therefore increasingly treated as a managerial capability challenge that influences competitive positioning and long-term performance outcomes (Lee et al., 2024). Importantly, emerging empirical evidence suggests that sustainability outcomes increasingly depend on coordination across supply chain partners, as environmental and operational collaboration within supply networks directly strengthens sustainable performance outcomes (Ahmed et al., 2020; Lee & Ha, 2020; Uddin & Akhter, 2022).

This dependency becomes particularly pronounced in manufacturing sectors operating within complex and tightly regulated supply networks. Global disruptions driven by pandemics, geopolitical instability, and regulatory fragmentation have exposed structural vulnerabilities in manufacturing supply chains, particularly in emerging economies characterised by institutional constraints, supplier concentration, and limited digital maturity (Awuah-Gyawu et al., 2025; Le et al., 2025; Zhou et al., 2024). Under such conditions, firms must balance sustainability objectives with supply continuity and operational stability across supply networks. Consequently, sustainable performance (SP) is increasingly contingent on firms' ability to develop collaborative supply chain practices that align environmental objectives with operational requirements across the supply network (Javed et al., 2024; Uddin & Akhter, 2022).

The pharmaceutical manufacturing sector provides a highly regulated context that exemplifies these challenges. Pharmaceutical production relies on energy intensive processes and stringent quality assurance requirements, which generate substantial environmental burdens and limit operational flexibility. At the supply chain level, these pharmaceutical networks operate under strict regulatory controls and highly structured sourcing arrangements, reducing firms' ability to rapidly reconfigure suppliers or material flows in response to disruptions (Badejo & Ierapetritou, 2024). Recent evidence further indicates that pharmaceutical supply chains remain vulnerable to global shocks due to concentrated upstream sourcing and compliance driven rigidity, which can undermine continuity and sustainability related performance outcomes (Mastrantonas et al., 2024; Poku et al., 2025).

In emerging economies such as Indonesia, these vulnerabilities are further intensified by structural import dependence within pharmaceutical supply chains. More than 90 percent of active pharmaceutical ingredients used in domestic pharmaceutical production are sourced from overseas suppliers, creating chronic exposure to external supply shocks, price volatility, and geopolitical risk (Arief et al., 2022; Khan &

Rauf, 2024). Such dependency weakens supply continuity and reduces the ability of pharmaceutical systems to respond effectively to global disruptions. These patterns highlight the need for coordinated capability development across interconnected supply chain actors (Awuah-Gyawu et al., 2025; Le et al., 2025; Mastrantonas et al., 2024).

Addressing these challenges requires a shift from isolated sustainability initiatives toward the development of collaborative supply chain capabilities that extend beyond firm boundaries. Prior research indicates that sustainability related performance in complex manufacturing systems is shaped not only by internal environmental practices but by coordinated actions among supply chain partners that enable information sharing, joint planning, and resource integration across the network (Silva et al., 2023; Zhou et al., 2024). In this context, green supply chain collaboration (GSCC) represents an inter organizational capability that facilitates cross organisational cooperation in key supply chain activities and supports the alignment of environmental and operational objectives (Cheng et al., 2024). Empirical evidence further shows that collaboration among supply chain partners enhances firms' capabilities and contributes positively to social, economic, and environmental performance outcomes, indicating that sustainability improvements increasingly depend on coordinated actions across the supply network rather than isolated firm level initiatives (Ahmed et al., 2020; Billah et al., 2023). However, limited research explains how collaborative mechanisms translate sustainability initiatives into sustained performance outcomes in regulated supply chains (Zhou et al., 2024).

Digital transformation has been increasingly positioned as a critical enabler for strengthening supply chain capabilities in manufacturing contexts. I4.0 enhances data integration, process visibility, and real-time information flows, thereby supporting coordination, responsiveness, and adaptive decision making across supply chain networks (Cheng et al., 2024). However, evidence from emerging economies indicates that the adoption of I4.0 remains uneven, particularly in highly regulated industries such as pharmaceuticals, where validation requirements, skills constraints, and limited digital maturity restrict effective technological deployment (Arief et al., 2022; Mastrantonas et al., 2024). These conditions suggest that digital investments alone may not automatically translate into sustainable performance without complementary relational and knowledge integration mechanisms. Accordingly, I4.0 readiness must be complemented by KM capabilities that enable firms to acquire, integrate, and apply operational and inter organisational knowledge, thereby facilitating coordinated action with supply chain partners, which is central to the development of GSCC (Hashem et al., 2024; Zighan et al., 2024). Empirical evidence also shows that digital technologies and knowledge transfer strengthen collaboration among supply chain partners, supporting the development of GSCC (Rashid et al., 2024; Whitehead et al., 2019).

Although prior studies have examined the individual effects of I4.0 on SP (Jayashree et al., 2021; Shahzad et al., 2024), the role of GSCC in improving SP (Ahmed et al., 2020; Billah et al., 2023; Uddin & Akhter, 2022), and the contribution of KM to SP (Khan et al., 2024; Martínez-Falcó et al., 2023), limited attention has been devoted to explaining how I4.0 and KM jointly enable SP through GSCC. Existing research largely treats these capability domains in isolation, offering insufficient insight into both the direct performance implications of these capabilities and the relational processes through which they are converted into measurable SP outcomes. This limitation becomes particularly salient in highly regulated pharmaceutical supply chains, where institutional rigidity and structural sourcing constraints may condition the effectiveness of GSCC (Lee & Ha, 2020; Zhou et al., 2024). Recent pharmaceutical evidence further highlights the absence of comprehensive integrative frameworks that simultaneously incorporate knowledge management, supply chain sustainability practices, and resilience considerations within regulated supply networks (Zaman et al., 2025).

This study therefore advances the Relational View by positioning GSCC as the relational mechanism through which technological and knowledge capabilities are converted into sustainable performance. By empirically examining pharmaceutical manufacturing firms in Indonesia, this research investigates how I4.0 and KM enable GSCC and how this collaborative capability contributes to SP in regulated supply chains.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

This study draws on the resource based view (RBV) to explain how internal capabilities such as I4.0 and KM contribute to sustainable performance (Barney, 1991; Wernerfelt, 1984). I4.0 enhances information processing and operational integration, while KM supports knowledge sharing and organisational learning that strengthen coordination across supply chain activities (Chen et al., 2015; Kamble et al., 2020; Wei et al., 2022). These capabilities also facilitate GSCC by linking internal operational systems with collaborative sustainability practices across supply chain partners.

Extending RBV beyond firm boundaries, the Relational View suggests that collaborative relationships generate relational rents through joint resource deployment and coordinated actions among supply chain partners (Dyer & Singh, 1998). Integrating these perspectives, this study proposes that I4.0 and KM contribute to sustainable performance through GSCC as a relational capability that enables the conversion of internal technological and knowledge resources into sustainability outcomes across supply networks.

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2.1 The effects of Industry 4.0 and knowledge management on green supply chain collaboration

I4.0 represents a technological capability that integrates digital technologies such as IoT, data analytics, and automation to enhance information visibility and coordination across supply chain partners (Cheng et al., 2024; Gallo et al., 2023). From an RBV perspective, these digital resources improve operational integration and reduce information asymmetry, enabling firms to coordinate environmental practices with supply chain partners and strengthen green supply chain collaboration (Shahzad et al., 2024; Srivastava et al., 2024).

Similarly, KM represents an intangible capability that supports knowledge sharing, organisational learning, and coordinated decision making across supply chain partners (Nonaka et al., 1996). Effective knowledge integration improves collaborative planning and synchronisation of interdependent activities, thereby strengthening supply chain collaboration in complex and regulated environments (Hashem et al., 2024; Zighan et al., 2024). Accordingly, both I4.0 and KM are expected to facilitate GSCC across supply networks.

H1. I4.0 has a positive effect on GSCC.

H2. KM has a positive effect on GSCC.

2.2 The effect of green supply chain collaboration on sustainable performance

GSCC represents a relational capability that enables firms to share environmental information, coordinate sustainability initiatives, and align operational activities with supply chain partners (Cheng et al., 2024; Dyer & Singh, 1998). From the relational view, collaboration among supply chain partners provides access to complementary resources and coordinated response mechanisms that improve environmental efficiency and operational alignment across the supply network (Dyer & Singh, 1998). Empirical studies indicate that environmental collaboration with supply chain partners enhances operational, environmental, and financial performance, thereby supporting sustainable performance outcomes (Ahmed et al., 2020; Billah et al., 2023; Uddin & Akhter, 2022).

H3. GSCC has a positive effect on SP.

2.3 The effect of Industry 4.0 and knowledge management on sustainable performance

I4.0 contributes to SP by enhancing operational efficiency, resource utilisation, and environmental monitoring through advanced digital technologies (Alyahya et al., 2023; Buhaya & Metwally, 2024). From an RBV perspective, digital infrastructures such as big data analytics, automation, and interconnected production systems represent strategic technological resources that improve firms' ability to integrate sustainability considerations into operational processes (Barney, 1991; Teece et al., 1997). By enabling data-driven decision making and real-time process visibility, I4.0 supports waste reduction, energy efficiency, and improved environmental management across production and supply chain activities. Empirical evidence further indicates that digital transformation strengthens firms' economic, environmental, and social performance, reinforcing the role of I4.0 as a key capability for achieving long term SP (Felsberger et al., 2022).

Similarly, KM contributes to SP by enabling organisations to acquire, share, and apply knowledge that supports continuous improvement and sustainability oriented decision making (Nonaka, 1991; Nonaka et al., 1996) Within the RBV perspective, knowledge represents a strategic intangible resource that enhances organisational learning, operational efficiency, and environmental problem solving (Barney, 1991). Effective KM facilitates knowledge integration, supports innovation in sustainable practices, and strengthens organisational capabilities required for long term performance improvement. Empirical studies further show that firms with strong KM practices demonstrate improved sustainability outcomes through enhanced learning, coordination, and process optimisation (Martínez-Falcó et al., 2023; Nasir et al., 2024).

H4. I4.0 has a positive effect on SP.

H5. KM has a positive effect on SP.

2.4 The mediating effect of green supply chain collaboration

GSCC is conceptualised as a relational capability that enables firms to coordinate environmental initiatives, share resources, and align sustainability objectives across supply chain partners. In complex supply networks, technological resources rarely generate sustainability outcomes independently and instead require coordinated execution across organisational boundaries. Prior research shows that collaborative supply chain practices translate internal capabilities into sustainability related performance outcomes (Ahmed et al., 2020; Billah et al., 2023). Empirical evidence further indicates that GSCC mediates the relationship between digital capabilities and sustainability outcomes by linking technological resources with coordinated environmental practices across supply networks (Cheng et al., 2024; Rashid et al., 2024; Shahzad et al., 2024). Accordingly, the sustainability benefits of I4.0 are expected to be realised through GSCC as a relational mechanism that enables coordinated environmental execution among supply chain partners.

From a knowledge based perspective, KM enhances organisational performance when knowledge resources are shared and integrated across organisational boundaries rather than retained within individual units (Nonaka, 1991; Nonaka et al., 1996). Knowledge exchange among supply chain partners supports collaborative problem solving, improves relational alignment, and facilitates coordinated sustainability initiatives across supply networks (Haque & Islam, 2018; Whitehead et al., 2019). Empirical studies also show that collaborative environmental practices across suppliers and customers improve environmental and operational outcomes, thereby contributing to overall SP (Ahmed et al., 2020; Billah et al., 2023). Therefore, KM is expected to influence SP indirectly through GSCC as a relational capability that converts shared knowledge into coordinated sustainability practices across the supply network.

H6. GSCC mediates the relationship between I4.0 and SP.

H7. GSCC mediates the relationship between KM and SP.

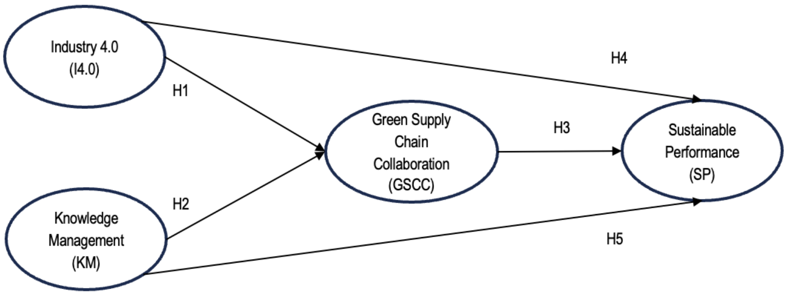

FIGURE 1. RESEARCH MODEL
Source: Authors' research (2025)

3. RESEARCH METHODOLOGY

This study employs a quantitative survey research design using primary data to examine the relationships among I4.0, KM, GSCC, and SP in pharmaceutical manufacturing firms in Indonesia. The unit of analysis is the individual manager because managers are directly involved in digitalisation initiatives, knowledge processes, supply chain coordination, and sustainability related decision making within their organisations. Data were collected through a structured questionnaire designed to capture respondents' perceptions of digitalisation practices, knowledge management processes, collaborative supply chain activities, and sustainability performance. All items were measured using a five point Likert scale ranging from strongly disagree to strongly agree.

The target population consisted of pharmaceutical manufacturing firms operating GMP certified injectable production facilities in Indonesia. This segment operates under strict regulatory requirements and complex supply chain structures, making it an appropriate empirical context for examining the roles of I4.0, KM, GSCC, and SP. A purposive sampling technique was applied to ensure that respondents had relevant managerial roles and sufficient knowledge regarding digitalisation and supply chain collaboration practices. The questionnaire was distributed online through professional networks, organisational contacts, and email communication. Data were collected between March and April 2025, during which approximately 600 questionnaires were distributed. After screening for completeness and response consistency, a total of 425 valid responses were retained for further analysis, representing a response rate of approximately 70.8%.

The constructs were measured using reflective indicators adapted from established scales. I4.0 capability was measured using items adapted from Shahzad et al. (2024). KM was operationalised through knowledge acquisition, conversion, application, and protection based on Gold et al. (2001) and Attia & Essam Eldin (2018). GSCC was measured using green information, resource, and strategic collaboration adapted from Cheng et al. (2024). SP included economic, environmental, and social performance dimensions measured using items from Jayashree et al. (2021) and Martínez-Falcó et al. (2024). Data were analysed using partial least squares structural equation modelling with SmartPLS following a two-stage approach consisting of measurement model evaluation and structural model assessment.

4. RESULTS

4.1 Respondent profile

Table 1 presents the demographic characteristics of the respondents. The sample mainly consists of managerial level employees holding bachelor's and master's degrees. The gender distribution is relatively balanced, while most respondents fall within the 31–40 and 41–50 age groups and possess substantial professional experience. These characteristics indicate that respondents have sufficient managerial knowledge and organisational involvement to provide reliable insights regarding the implementation of I4.0, KM, and collaborative supply chain practices.

TABLE 1. DEMOGRAPHIC DATA

Characteristic	Categories	Frequency	Percentage
Gender	Male	228	53.6%
	Female	197	46.6%
Age	< 25	1	0.2%
	25–30	84	19.8%
	31–40	192	45.2%
	41–50	131	30.8%
	>50	17	4.0%
Education	Bachelor	247	58.1%
	Masters	173	40.7%
	Doctorate	5	1.2%
Job Level	Manager	306	72.0%
	General Manager	99	23.3%
	Director	20	4.7%
	CEO	0	0%
Experience	1–2 years	31	7.3%
	3–5 years	120	28.2%
	6–8 years	141	33.2%
	9–10 years	79	18.6%
	>10 years	54	12.7%

Source: Authors' research (2025)

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4.2 Reliability and convergent validity

The measurement model demonstrates adequate reliability and convergent validity. As shown in Table 2, all outer loadings exceed 0.60, while Cronbach's Alpha and Composite Reliability values are above 0.70, confirming internal consistency. In addition, AVE values exceed 0.50 and VIF values remain below 3.3, indicating satisfactory convergent validity and no multicollinearity concerns.

TABLE 2. CONSTRUCT RELIABILITY, VALIDITY AND COLLINEARITY TEST RESULT

Dimension	Constructs, details of measures, and results of validity and reliability tests	Outer loading	VIF
	Industry 4.0 (AVE= 0.520, Rho_a = 0.873, CR = 0.896, CA =0.868)	0.721	1.714
	Adopting Industry 4.0 technology is significant for the pharmaceutical sector, particularly regarding supply chain flow	0.781	1.965
	I believe that applications for Industry 4.0 can improve the pharmaceutical industry's supply chain efficiency	0.743	1.915
	Using a variety of Industry 4.0 applications gives our company a stronger competitive edge	0.715	1.729
	Our workforce has received training to use Industry 4.0 applications effectively	0.735	1.712
	Our company has adopted the newest technology, including big data analytics, blockchain, AI, and IoT	0.751	1.944
	Development of an artificial intelligence-based risk management system that works well	0.667	1.714
	Development of a blockchain-based financial control system that works well	0.721	1.645
	Applications of Industry 4.0 during any crisis, the pharmaceutical industry's supply chain operations can be managed with the aid of IoT and big data analytics	0.721	1.496
	Knowledge management (AVE= 0.516, Rho_a = 0.916, CR = 0.927, CA =0.915)		
Knowledge Acquisition (mean =4.004)	Our organisation has clear rules for formatting or categorizing its product knowledge.	0.726	1.810
	Our organisation members use technology to search for new knowledge	0.749	2.304
	Our organisation members use technology to retrieve knowledge about its products and process	0.724	1.933
Knowledge Conversion (mean=3.998)	Our organisation structure facilitates the discovery of new knowledge	0.677	1.606
	Our organisation facilitates knowledge exchange across functional boundaries	0.745	2.055
	Our organisation members are encouraged to interact with other groups.	0.695	1.843
Knowledge Application (Mean = 3.994)	Our organisation members use technology to cooperate with other persons inside the organization.	0.717	1.964
	Our organisation members can understand not only their own tasks but also others' tasks.	0.755	2.289
	Our organisation members can communicate well not only with their department members but also with other department members.	0.727	2.088
Knowledge Protection (Mean=4.026)	Our organisation has a reward system for sharing knowledge.	0.664	1.769
	Our organisation's employees are readily accessible.	0.671	1.621
	Our organisation's members are specialists in their own part.	0.758	2.182
	Green Supply Chain Collaboration (AVE= 0.514, Rho_a = 0.934, CR = 0.941, CA =0.932)		
Green Information Collaboration	Our company has shared knowledge and information related to green technologies with upstream and downstream partners.	0.696	2.103
	Our company has shared knowledge and information related to green	0.724	2.141

(Mean =3.976)	production and processing with upstream and downstream partners.		
	Our company has shared experience, knowledge and information related to green product operations and management with upstream and downstream partners.	0.723	2.039
	Our company has shared knowledge and information related to green product marketing with upstream and downstream partners.	0.743	2.316
	Our company has shared the latest research reports and trends in the industry with upstream and downstream partners.	0.733	2.343
Green Resource Collaboration (Mean=3.926)	Our company has shared equipment, technology, talent and other resources with upstream and downstream partners.	0.706	2.037
	Our company has made full use of existing green resources to expand the business field with upstream and downstream partners.	0.756	2.576
	Our company has developed new green resources in new business fields jointly with upstream and downstream partners.	0.711	2.077
	Our company has developed new products or provided new services using new green resources jointly with upstream and downstream partners.	0.739	2.203
	Our company has obtained new green resources from the outside to grow existing business fields jointly with upstream and downstream partners.	0.721	2.001
Green Strategic Collaboration (Mean=3.947)	Our company maintains long-term and stable cooperative relations with upstream and downstream partners.	0.704	2.045
	Our company has achieved a common strategic goal of environmental protection with upstream and downstream partners.	0.637	1.771
	Our company has formulated strategic plans for green production, sales, research and development jointly with upstream and downstream partners.	0.735	1.989
	Our company has made strategic decisions and developed solutions to problems jointly with upstream and downstream partners.	0.708	1.962
	Our company has formed a common coordination mechanism in terms of costs, benefits and risks with upstream and downstream partners.	0.714	2.110
	Sustainability performance (AVE= 0.584, Rho_a = 0.946, CR = 0.952, CA =0.945)		
Economic Sustainability (Mean=3.997)	Our company's average return on investment is above the industry average over the past five year	0.757	2.232
	Our company's average profit is above the industry average over the last five years	0.736	2.221
	Our company's profit growth is above the industry average over the last five years.	0.791	2.530
	Our company's average sales profitability is above the industry average over the last five years	0.722	2.093
	Our company has decreased the cost of energy consumption by implementing industry 4.0	0.780	2.622
Social Sustainability (Mean=4.059)	Our company has improved the well-being of its stakeholders compared to its competitors over the last five years	0.757	2.158
	Our company has improved the health and safety of the community in which it operates relative to its competitors over the past five years	0.730	2.133
	Our company has reduced its environmental impact and risks to the general public relative to its competitors over the past five years	0.778	2.412
	Our company has provided health and safety requirements for the employees to achieve sustainability	0.742	2.059
	Our company has developed new products that reduce health risk for consumers to achieve sustainability by implementing industry 4.0	0.798	2.682
Environment	Our company has reduced waste and emissions from operations relative	0.779	2.448

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Sustainability (Mean=4.020)	to its competitors over the past five years		
	Our company has reduced the environmental impact of its products/services relative to its competitors over the past five years	0.791	2.556
	Our company has reduced energy consumption to achieve sustainability by implementing industry 4.0	0.782	2.565
	Our company has decreased the consumption of materials to achieve sustainability by implementing industry 4.0	0.753	2.326

Source: Author's research (2025)

4.3 Discriminant validity

Discriminant validity was evaluated using the Heterotrait Monotrait ratio (HTMT). As shown in Table 3, all HTMT values are below the conservative threshold of 0.85, confirming that I4.0, KM, GSCC, and SP represent empirically distinct constructs.

TABLE 3. HETEROTRAIT-MONOTRAIT RATIO (HTMT)

Variable	I4.0	KM	GSCC	SP
I4.0				
KM	0.287			
GSCC	0.461	0.263		
SP	0.733	0.238	0.442	

Source: Authors' research (2025)

4.4 Structural model evaluation

Model fit and explanatory power were assessed to evaluate the structural model. The SRMR values of 0.049 for the saturated model and 0.052 for the estimated model are below the recommended threshold of 0.08, indicating acceptable model fit.

The coefficient of determination (R^2) shows that I4.0 and KM explain 19.7% of the variance in GSCC, while GSCC explains 56.0% of the variance in SP. These values indicate moderate to substantial explanatory power and confirm that the model provides adequate predictive capability for subsequent hypothesis testing.

4.5 Hypothesis testing result

The structural model results are presented in Table 4. The findings show that I4.0 has a significant positive effect on GSCC ($\beta = 0.381$, $p < 0.001$), and KM also positively influences GSCC ($\beta = 0.150$, $p = 0.003$). These results indicate that both digital capability and organisational knowledge processes strengthen collaborative environmental practices within supply chains.

GSCC further demonstrates a significant positive effect on SP ($\beta = 0.113$, $p = 0.022$). In addition, I4.0 has a direct positive effect on SP ($\beta = 0.371$, $p < 0.001$), confirming the role of digital transformation in enhancing sustainability outcomes. However, the direct effect of KM on SP is not significant (β = 0.021, p = 0.305).

The mediation analysis shows that GSCC significantly mediates the relationship between I4.0 and SP (β = 0.043, p = 0.004). In contrast, the mediating effect of GSCC on the relationship between KM and SP is not supported (β = 0.017, p = 0.055).

TABLE 4. HYPOTHESIS TESTING RESULT

Path	Coefficient β	t-values	p-values	Results
Direct Effect				
H1 I4.0 → GSCC	0.381	5.475	0.000	Supported
H2 KM → GSCC	0.150	2.725	0.003	Supported
H3 GSCC → SP	0.113	2.008	0.022	Supported
H4 I4.0 → SP	0.371	4.976	0.000	Supported
H5 KM → SP	0.021	0.510	0.305	Not Supported
Mediating Effect				
H6 I4.0→GSCC→SP	0.043	1.794	0.004	Supported
H7 KM→GSCC→SP	0.017	1.598	0.055	Not Supported

Source: Authors' research (2025)

5. DISCUSSION

The findings indicate that I4.0 has a positive effect on GSCC. This suggests that digital technologies enhancing visibility, data integration, and connectivity across organisations facilitate environmental collaboration among supply chain partners. In highly regulated pharmaceutical supply chains, digitalisation improves information transparency and coordination, allowing firms to align sustainability practices and reduce information asymmetry across the network (Cheng et al., 2024; Gallo et al., 2023).

KM is also found to have a positive effect on GSCC. This indicates that organisational capabilities to acquire, share, and apply knowledge contribute to stronger collaborative relationships among supply chain partners. Knowledge exchange helps firms develop shared understanding and coordinate sustainability initiatives more effectively across organisational boundaries (Hashem et al., 2024; Whitehead et al., 2019).

Furthermore, GSCC has a positive effect on SP. These results suggest that sustainability performance in the pharmaceutical sector depends not only on internal organisational initiatives but also on the effectiveness of environmental coordination across supply chain partners. Strategic, informational, and resource collaboration allow firms to synchronise sustainability practices, improve operational efficiency, and reduce environmental impacts (Ahmed et al., 2020; Billah et al., 2023).

The results also show that I4.0 has a direct positive effect on SP, whereas KM does not have a significant direct influence on SP. This finding indicates that digital transformation can directly enhance sustainability performance by improving traceability, process transparency, and data-driven operational monitoring.

Technologies such as IoT, big data analytics, and automation allow firms to track resource usage, identify inefficiencies, and implement more responsive operational improvements.

In contrast, the non-significant relationship between KM and SP suggests that knowledge resources alone may not automatically translate into sustainability outcomes in highly regulated pharmaceutical environments. Strict documentation requirements, procedural formalisation, and multi-layer approval processes often slow the implementation of new practices. As a result, knowledge capabilities may support coordination and information exchange but may not directly lead to measurable improvements in sustainability performance.

The mediation analysis further shows that GSCC mediates the relationship between I4.0 and SP. This indicates that digital technologies contribute to sustainability not only through internal operational improvements but also through collaborative mechanisms that coordinate environmental practices across supply chain partners (Gallo et al., 2023; Rashid et al., 2025).

However, GSCC does not mediate the relationship between KM and SP. Although KM supports the development of collaboration, the indirect effect on sustainability performance is not significant. This suggests that knowledge sharing alone is insufficient to generate sustainability outcomes unless it is supported by deeper integration and coordinated actions among supply chain partners.

6. IMPLICATIONS

6.1 Theoretical contribution

This study provides theoretical contributions to the literature on digital transformation and sustainable performance. First, the findings extend the Relational View by showing that sustainable performance in highly regulated supply chains is not determined solely by firms' internal capabilities but is also shaped by inter organizational collaboration through GSCC. Second, the study supports the Resource Based View by confirming that digital capability represented by I4.0 functions as a strategic resource that directly enhances sustainable performance. Third, the study enriches the Knowledge Based View by indicating that knowledge capabilities do not automatically lead to sustainable performance without effective integration within collaborative supply chain practices.

6.2 Managerial implication

Managers in pharmaceutical manufacturing firms can draw several practical implications from these findings. Managers should prioritise Industry 4.0 investments that enhance digital traceability, real-time monitoring, and information integration across supply chain activities, as these technologies improve operational transparency and enable firms to optimise resource utilisation and sustainability performance. Firms should also strengthen green supply chain collaboration by promoting environmental information sharing, joint sustainability initiatives, and the development of green resource collaboration with key suppliers and logistics partners. Although KM supports collaboration, knowledge resources should be translated into practical routines and coordinated actions rather than remaining primarily as documentation, enabling firms to implement sustainability initiatives more effectively.

7. CONCLUSION

This study examines the roles of I4.0, KM, and GSCC in improving SP in pharmaceutical manufacturing firms in Indonesia. The results indicate that I4.0 has a significant direct effect on SP and also contributes to the development of GSCC, whereas KM does not show a significant direct effect on SP. In addition, GSCC mediates the relationship between I4.0 and SP, although the direct effect of I4.0 on SP remains stronger than the mediated pathway. These findings highlight I4.0 as a key driver of sustainable performance in the pharmaceutical industry.

8. LIMITATION AND FUTURE RESEARCH

This study has several limitations that should be acknowledged. First, the analysis is limited to pharmaceutical manufacturing firms in Indonesia, which may restrict the generalisability of the findings to other industries or contexts with different regulatory environments. Second, the cross-sectional research design limits the ability to capture the dynamic development of I4.0, KM, GSCC, and SP over time. Third, although GSCC is found to mediate the relationship between I4.0 and SP, its explanatory power remains moderate, indicating that other relevant drivers of GSCC may not have been fully captured in the model.

Future research could extend this study by examining additional determinants of GSCC, such as digital readiness, supply chain integration, and organisational capabilities related to sustainability. Further studies may also explore the role of I4.0 and KM in different industrial contexts to assess the consistency of their effects on SP. In addition, longitudinal research designs are recommended to better understand how I4.0 and KM contribute to the development of GSCC and its impact on SP over time.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing and improving the clarity of the manuscript. After using this tool, the authors carefully reviewed and revised the content and take full responsibility for the final version of the published article.

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