current perspective on business operations

e-ISSN: 3125-1323

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Knowledge Dynamics as a Bridge Between Green Supply Chain Integration and Green Innovation

Amalia Desta Fitri Pramono [1*]

[1] College of Management, National Yunlin University of Science and Technology; amalia.pramono21@gmail.com

* Correspondence: amalia.pramono21@gmail.com

Abstract
This study investigates the influence of green supply chain integration (GSCI) on both green incremental innovation (GII) and green radical innovation (GRI) within manufacturing firms. In particular, the research explores the mediating roles of complementary knowledge coupling (CKC) and new knowledge diffusion (NND), while also examining the moderating effect of green technology turbulence (GTT) on these relationships. Data were collected through a cross-sectional survey involving 376 managers from manufacturing companies in Pakistan and analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The findings reveal that GSCI positively contributes to both GII and GRI, with a stronger effect observed for incremental innovation. Furthermore, CKC and NND significantly mediate the relationship between GSCI and both forms of green innovation by facilitating the integration, transfer, and utilization of knowledge across organizational boundaries. The results also indicate that GTT strengthens the relationship between GSCI and GRI, whereas its moderating effect on GII is not significant. These findings suggest that organizations can enhance their innovation performance by fostering collaborative supply chain relationships, strengthening knowledge-sharing mechanisms, and developing adaptive capabilities to respond to technological uncertainty. Beyond managerial implications, the study highlights the role of knowledge-driven green supply chain practices in supporting environmental sustainability and responsible production. By uncovering the interconnections among GSCI, CKC, NND, GTT, and green innovation, this research provides a novel contribution to the green innovation and knowledge management literature and offers a deeper understanding of how knowledge-based capabilities facilitate sustainable innovation outcomes.

Keywords: Green supply chain integration; incremental green innovation; radical green innovation; knowledge-based view; green technology turbulence.

Academic Editor: Daniel Wang

Received: April 28, 2026 | Revised: May 22, 2026 | Accepted: June 10, 2026 | Published: June 22, 2026

Citation: Pramono, A. D. F. (2026). Knowledge dynamics as a bridge between green supply chain integration and green innovation. *Current Perspective on Business Operations*, *2*(3), 249-269.

1. Introduction

Industrial pollution has emerged as one of the most pressing global environmental challenges, largely fueled by rapid industrialization and the expansion of manufacturing activities. As manufacturing firms continue to generate substantial waste and consume significant natural resources, traditional production approaches have become increasingly inadequate in addressing environmental degradation and sustainability concerns (Javed et al., 2024c). Consequently, green innovation (GI) has gained considerable attention as a strategic approach for reducing ecological impacts while supporting sustainable industrial development. Green innovation generally encompasses two dimensions: green incremental innovation (GII) and green radical innovation (GRI) (Chen et al., 2014b; Dai et al., 2015). Green incremental innovation focuses on gradual improvements to existing environmentally friendly products, services, and processes, whereas green radical innovation involves transformative technological breakthroughs that fundamentally reshape environmental practices and capabilities.

Given the complexity and knowledge-intensive nature of both GII and GRI, organizations increasingly require access to diverse sources of knowledge that extend beyond traditional innovation resources (Al-Swidi et al., 2023b). In this regard, green supply chain integration (GSCI) has emerged as an important mechanism that enables firms to collaborate closely with suppliers, customers, and other supply chain partners to facilitate knowledge sharing and environmental innovation (Kong et al., 2020; Javed et al., 2025). Despite growing scholarly interest in GSCI, limited evidence exists regarding how it influences different forms of green innovation, particularly green incremental and radical innovation (Kong et al., 2020; Javed et al., 2024b). From a knowledge-based perspective, firms serve as repositories and integrators of valuable knowledge resources (Liu et al., 2024; Basit et al., 2024). However, previous studies have paid insufficient attention to the role of GSCI as a strategic channel through which organizations acquire and utilize knowledge to foster both GII and GRI (Shehzad et al., 2021). Therefore, the specific mechanisms through which GSCI contributes to green innovation remain underexplored.

One potential mechanism is complementary knowledge coupling (CKC), which refers to a firm's ability to acquire critical knowledge from external partners and combine it with internal knowledge resources to generate innovative outcomes and support the exploration of new ideas (Zhao et al., 2024). Existing studies emphasize the significance of knowledge coupling in stimulating innovation by integrating heterogeneous knowledge domains. Nevertheless, most investigations have concentrated on technological settings, while the role of knowledge coupling within collaborative supply chain relationships remains insufficiently understood (Zhao et al., 2024; Chen et al., 2024). Consequently, examining the mediating role of CKC may provide valuable insights into how GSCI contributes to different forms of green innovation.

Another important mechanism is new knowledge diffusion (NND), which involves the dissemination and transfer of newly generated knowledge across individuals, teams, and organizational units to facilitate innovation development (Chiu et al., 2024). Knowledge diffusion enables organizations to leverage both explicit and tacit knowledge from internal and external sources, thereby strengthening collaboration, enhancing creativity, and improving innovation capabilities (Zhang et al., 2024; Zia et al., 2024; Javed et al., 2025). Previous research suggests that NND supports open innovation initiatives and enhances firms' ability to generate innovative outcomes (Sedita et al., 2021). However, challenges associated with knowledge sharing and adoption continue to hinder innovation performance, highlighting the need to investigate how the diffusion of new knowledge mediates the relationship between GSCI and green innovation (Chiu et al., 2024).

In addition to internal knowledge mechanisms, external environmental conditions may also shape the effectiveness of green innovation initiatives. Green technology turbulence (GTT) represents the rate and unpredictability of technological changes within environmentally oriented markets and industries, creating uncertainty and challenges for firms seeking to implement sustainable innovations (Lisi et al., 2020). Because green innovation often depends on substantial internal and external support, firms operating in turbulent technological environments face greater difficulties in developing environmentally friendly products and processes (Javed et al., 2024b; Al-Swidi et al., 2023a). Prior studies have examined the moderating role of GTT in relationships involving green entrepreneurial orientation, green supply chain learning, green market orientation, and green product innovation performance (Lisi et al., 2020; Al-Swidi et al., 2023a; Hossain et al., 2024; Aboalhool et al., 2024; Ta'amnha et al., 2024). Nevertheless, empirical findings remain inconclusive regarding how technological turbulence influences green innovation outcomes (Javed et al., 2024b; Aboalhool et al., 2024), indicating the need for further investigation.

The manufacturing sector in Pakistan provides an appropriate context for exploring these relationships because environmental regulations and sustainability practices are still evolving, and firms frequently rely on industry norms rather than stringent regulatory requirements to guide environmental initiatives (Basit et al., 2024). This context offers a unique opportunity to understand how organizations develop green innovation strategies in environments characterized by relatively flexible institutional pressures. Accordingly, this study makes three important contributions. First, it develops a comprehensive framework that explains how GSCI influences both green incremental and radical innovation, addressing a significant gap in the existing literature (Javed et al., 2024b; Al-Swidi et al., 2024). Second, it extends prior research by examining the roles of complementary knowledge coupling and new knowledge diffusion as mediating mechanisms linking GSCI with green innovation outcomes. Third, unlike previous studies that primarily rely on the resource-based view and information processing theory (Riaz et al., 2023; Al-Swidi et al., 2023b; Javed et al., 2024c; Zhou et al., 2023), this study integrates the knowledge-based view (KBV) and contingency theory (CT) to explain how firms utilize knowledge resources and adapt to environmental conditions in promoting green incremental and radical innovation. Through this theoretical integration, the study advances the understanding of green innovation in manufacturing firms and provides new insights into the interplay between knowledge capabilities, supply chain integration, and environmental uncertainty.

2. Literature Review

This study is grounded in the knowledge-based view (KBV) and contingency theory (CT). The KBV emphasizes knowledge as a critical strategic resource that supports economic growth, organizational competitiveness, and innovation performance (Riaz et al., 2023). Within this perspective, knowledge enables firms to store, acquire, generate, and apply strategic resources for decision-making and innovation development (Pereira & Bamel, 2021; Hughes et al., 2022). Green supply chain integration (GSCI) can therefore be understood as a dynamic capability that strengthens a firm's ability to acquire, synthesize, and utilize dispersed knowledge from internal functions and external supply chain partners. By connecting internal units with suppliers and customers, GSCI helps reduce knowledge stickiness and supports knowledge recombination, which is essential for green incremental innovation (GII) and green radical innovation (GRI).

In the KBV framework, complementary knowledge coupling (CKC) reflects the integration and reconfiguration of diverse knowledge resources to align internal and external knowledge domains and enhance innovation capabilities (Liu et al., 2024). Meanwhile, contingency theory argues that no single organizational approach is universally effective; rather, firm performance depends on the alignment between internal structures, organizational processes, and external environmental conditions (Lawrence & Lorsch, 1967). Green technology turbulence (GTT) represents a key contingency factor because it creates unexpected risks and uncertainties in green technological markets (Al-Swidi et al., 2023a). Firms facing high GTT must adapt their internal structures, innovation processes, supply networks, R&D priorities, and decision-making systems to remain aligned with external technological change. Thus, GSCI functions as a strategic mechanism that enables firms to respond to environmental disruption and maintain innovation alignment.

In Pakistan's manufacturing sector, GSCI is particularly important because firms operate under evolving institutional infrastructure, inconsistent policy enforcement, limited resources, and fragmented supply chain systems. These constraints hinder smooth knowledge exchange and weaken innovation performance. Through GSCI, firms can align dispersed resources, overcome structural inefficiencies, and adapt their knowledge strategies to support green innovation. This context strengthens the relevance of both KBV and CT in explaining how manufacturing firms in emerging economies develop green innovation capabilities. In addition, supply chain resilience (SCR) provides a complementary perspective by emphasizing firms' capacity to manage disruption and maintain long-term operational continuity (Mishra & Singh, 2022). Prior studies have highlighted resilience as a key factor in daily operational stability and long-term sustainability (Pettit et al., 2019), while technology-enabled visibility, core resilience capabilities, risk-mitigation culture, transparency, cooperation, agility, and sustainability-oriented strategies have been identified as essential drivers of resilient green supply chains (Faggioni et al., 2024; Kumar & Anbanandam, 2019).

Green incremental innovation refers to continuous improvements in existing products, services, and processes that enhance environmental sustainability without fundamentally altering core structures (Bai et al., 2024). Incremental innovation depends on a firm's ability to integrate internal and external knowledge resources to strengthen continuous improvement and competitiveness (Idrees et al., 2023). Because green innovation involves uncertainty, firms require effective GSCI to integrate knowledge from upstream and downstream partners (Javed et al., 2024c; Al-Swidi et al., 2024). Internal and external integration allow firms to access critical green resources, utilize suppliers' environmental knowledge, and collaborate with customers to align green objectives and improve existing products (Zhou & Zhao, 2024). However, recent evidence suggests that the effect of integration may vary, as internal integration may improve innovation, whereas supplier and customer integration may produce adverse effects under certain conditions (Zhou & Mei, 2025). Accordingly, this study proposes that green supply chain integration positively affects green incremental innovation.

Green radical innovation refers to more substantial environmental breakthroughs that require firms to depart from existing practices and develop new eco-friendly products, services, or processes (Cancela et al., 2023; Bai et al., 2024). GSCI can support radical innovation by fostering collaboration, sustainable knowledge sharing, and access to green resources across supply chain partners (Javed et al., 2024b). However, prior studies indicate that GSCI may more consistently support incremental rather than radical innovation because exploratory activities do not always produce strong outcomes compared with exploitative efforts (Yang et al., 2024). When firms lack the capability to convert exploratory ideas into breakthrough innovations, the influence of integration on radical innovation may weaken (Sun & Sun, 2021). In addition, early-stage radical innovation may initially reduce performance before producing benefits, suggesting that the relationship between exploratory innovation and firm outcomes can be nonlinear and capability-dependent (Xie et al., 2022). Since radical innovation is riskier and more complex, it relies heavily on cross-boundary knowledge exchange and collaboration with external partners (Ritala et al., 2018). Therefore, this study proposes that green supply chain integration positively affects green radical innovation.

Complementary knowledge coupling refers to the process through which firms acquire missing knowledge from collaborative partners and integrate it with existing internal resources (Zhao et al., 2024; Chen et al., 2024). Collaboration with suppliers and customers enables firms to conduct knowledge-related activities and integrate diverse expertise. External sources offer complementary knowledge, while internal employee involvement, coordination, and organizational orientation facilitate the integration of that knowledge within the firm (Liu et al., 2024). Since both external and internal sources are essential for knowledge coupling, collaboration and coordination help firms address environmental challenges and achieve shared green objectives (Javed et al., 2024b). Thus, this study proposes that green supply chain integration positively affects complementary knowledge coupling.

New knowledge diffusion (NND) refers to the transfer of explicit and tacit knowledge from individuals to teams and across organizational units (Chiu et al., 2024). Customer interaction enables firms to acquire valuable insights, develop new expertise, refine existing capabilities, and respond to complex market demands (Shehzad et al., 2021). GSCI promotes the exchange of novel knowledge through continuous collaboration among firms, suppliers, and customers, enabling the generation of new perspectives and the integration of eco-friendly practices (Javed et al., 2024b). Interpersonal relationships, collaboration, loyalty, and active employee involvement further support effective knowledge diffusion within organizations (Chiu et al., 2024). Supplier and customer integration also facilitate the diffusion of new knowledge through real-time information exchange, technological insights, and green market knowledge (Zhou et al., 2023). Therefore, this study proposes that green supply chain integration positively affects new knowledge diffusion.

Knowledge capabilities are also expected to influence green innovation outcomes. CKC enables firms to evaluate, synthesize, and use knowledge more effectively in innovation processes, while strengthening specialization within existing technological domains (Dibiaggio et al., 2014). Incremental innovation often emerges from the integration of diverse technological knowledge domains and the continuous refinement of a firm's existing knowledge base (Liu et al., 2024; Zhou et al., 2023). Recombining knowledge to address new environmental demands can improve existing products and make them more sustainable (Zhao et al., 2024). Accordingly, CKC is expected to enhance green incremental innovation by optimizing the use of existing knowledge and resources. CKC may also support green radical innovation because it enables firms to reorganize technological expertise, redirect R&D trajectories, broaden knowledge combinations, and overcome existing knowledge limitations (Caner & Tyler, 2015; Liu et al., 2024; Zhao et al., 2024; Chen et al., 2024). Therefore, this study proposes that complementary knowledge coupling positively affects both green incremental and green radical innovation.

NND is also expected to contribute to green innovation. The diffusion of explicit and tacit knowledge across employees, teams, and organizational units enables firms to preserve and enhance employee expertise, strengthen learning processes, and support innovation development (Chiu et al., 2024; Barba-Aragón & Jiménez-Jiménez, 2024; Zia et al., 2024). Firms must generate and disseminate new knowledge during the knowledge search process because it broadens idea generation and encourages creative development (Zhong & Luo, 2018). In this sense, NND provides critical information and expertise for developing green products, green technologies, and adaptive responses to disruptive environments. Furthermore, knowledge diffusion supports market and product development, strategic planning, and innovation capability enhancement (Sedita et al., 2021; Eryarsoy et al., 2022). Since breakthrough green innovation requires firms to integrate internal and external insights with evolving technologies and market trends, NND is expected to support both green incremental and radical innovation (Al-Swidi et al., 2024; Zhong & Luo, 2018).

This study further proposes that CKC and NND mediate the relationship between GSCI and green innovation. Strong knowledge coupling reflects robust linkages among the knowledge resources of different entities, enabling firms to combine internal and external knowledge to generate technological innovations (Chen et al., 2024). Complementary knowledge begins with the assimilation of external knowledge, which is then integrated with internal expertise to create a cohesive knowledge system capable of bridging knowledge gaps, restructuring resources, and producing new solutions (Liu et al., 2024). Similarly, integrating diverse knowledge resources enables firms to reconfigure internal and external expertise and drive transformative organizational change (Zhao et al., 2024). Therefore, CKC is expected to positively mediate the relationship between GSCI and both GII and GRI. NND also plays a mediating role because it enables rapid knowledge transfer through communication, coordination, and stakeholder collaboration (Chiu et al., 2024). Knowledge acquisition, sharing, and implementation allow firms to accelerate product development and advanced production control technologies (Shehzad et al., 2021), while inter-organizational collaboration helps firms acquire and assimilate customer and supplier knowledge for radical innovation (Zhou et al., 2023). Therefore, NND is expected to positively mediate the relationship between GSCI and both forms of green innovation.

GTT is examined as a moderating variable. In technologically turbulent environments, firms seek advanced technologies and critical knowledge through collaboration with external partners (Cai et al., 2014). Such turbulence encourages firms to adopt advanced technologies, integrate with external partners, acquire novel solutions, and adapt to technological change (Ivanov & Dolgui, 2021; Al-Swidi et al., 2023a; Javed et al., 2024b). Prior research suggests that technological turbulence may strengthen the relationship between eco-innovative products and performance because firms must rapidly acquire knowledge and adopt innovative solutions to remain competitive (Ta'amnha et al., 2024). GTT has also been found to moderate the relationship between environmental customer learning and green product and process innovation (Lisi et al., 2020). However, some studies show that this moderating role is not always significant, particularly in contexts where firms have limited absorptive capacity or weak institutional support (Wu, 2013). Accordingly, this study proposes that green technology turbulence positively moderates the relationship between GSCI and both green incremental and green radical innovation.

3. Research Methods

This research employed a cross-sectional survey design targeting large manufacturing firms in Pakistan. The manufacturing sector was selected because of its substantial environmental impact and its critical role in climate change, resource depletion, and pollution (Javed et al., 2024c). Data were collected between July and November 2024 through a structured questionnaire distributed to large manufacturing firms, defined as firms with more than 200 employees. Firms were randomly selected from the Securities and Exchange Commission of Pakistan's list. Large firms were selected because they are more likely to generate measurable green innovation outcomes and possess the resources needed to support green initiatives. Respondents were contacted by telephone, email, and, when necessary, in-person visits to explain the purpose of the study and request participation. A total of 394 responses were obtained, of which 376 were complete and met the inclusion criteria, representing a response rate of 61.64%. Eighteen responses were excluded due to excessive missing data. The final respondents consisted mainly of managers from supply chain, procurement, production, and R&D departments, representing industries such as textiles, chemicals, pharmaceuticals, food manufacturing, and related manufacturing sectors.

Table 1. Respondent's Profile

Variable	Category	Frequency	Percentage (%)
Gender	Male	238	63.3
	Female	138	36.7
Age	25–30 years	91	24.2
	31–35 years	96	25.5
	36–40 years	106	28.2
	Above 41 years	83	22.1
Job Title	Supply Chain Officer	115	30.6
	Supply Chain Executive	78	20.7
	Vendor/Procurement Officer	101	26.8
	Logistics Coordinator	82	21.8
Education	Undergraduate	150	39.9
	Graduate	181	48.1
	Postgraduate	45	12.0
Industry Sector	Surgical	24	6.3
	Textile	15	3.8
	Sports	13	3.5
	Leather	17	4.5
	Sugar	16	4.3
	Pharmaceuticals	20	5.3
	Steel	22	5.9
	Food & Beverages	13	3.5
	Electronics	18	4.8
	Aerospace & Defense	10	2.7
	Chemicals	19	5.1
	Luxury Goods	24	6.4
	Construction Equipment	23	6.1
	Tires	18	4.8
	Motor Vehicles & Parts	20	5.3
	Industrial Machinery	25	6.7
	Telecommunications Equipment	18	4.8
	Wood and Furniture	20	5.3
	Other	41	10.9
Job Experience	Less than 5 years	102	27.1
	6–9 years	143	38.0
	10–14 years	97	25.8
	Above 14 years	34	9.0

The survey instrument was developed through several stages, with attention to wording, response format, measurement type, question sequence, and the broader research context. The questionnaire consisted of two parts. The first section collected demographic information, while the second section measured the main constructs. The initial items were adapted from established scales and refined through interviews with four senior academic researchers to ensure face validity. GSCI was measured using nine items adapted from Javed et al. (2024b), Al-Swidi et al. (2024), and Javed et al. (2025). Although GSCI includes supplier, customer, and internal integration, it was treated as a unidimensional construct to maintain parsimony, consistent with prior studies (Javed et al., 2024b). The measurement items were designed to reflect all three dimensions of integration. NND was measured using four items from Chiu et al. (2024), CKC using four items from Zhao et al. (2024), GII using six items from Zhou et al. (2023) and Idrees et al. (2023), GRI using six items from Idrees et al. (2023) and Chen et al. (2014a), and GTT using four items from Al-Swidi et al. (2023a) and Aboalhool et al. (2024).

Table 2. Summary of Constructs

Construct	Item	Measurement Item	Source
Green Supply Chain Integration (GSCI)	GSCI1	Our firm works toward meeting environmental objectives in partnership with its suppliers.	Javed et al. (2024b); Al-Swidi et al. (2024); Javed et al. (2025)
	GSCI2	Our firm endeavors to collaborate with suppliers in planning to identify, address, and enhance environmental performance of existing green products.	
	GSCI3	Our firm collaborates closely with suppliers to make informed decisions that focus on transforming our products and processes, aiming to significantly reduce environmental impact.	
	GSCI4	Our firm engages with consumers in joint planning to proactively address and solve environmental-related issues.	
	GSCI5	Our company seeks to make collaborative decisions with customers on improving existing products to reduce their environmental impact.	
	GSCI6	Our firm actively engages with customers in discussions and communication to gain market insights and understand their needs for improving green products.	
	GSCI7	Our firm develops corporate culture that is committed to environmental accountability.	
	GSCI8	Our company works toward accomplishing environmental objectives through the active input, communication, and involvement of employees across various departments.	

Construct	Item	Measurement Item	Source
	GSCI9	The firm's management collaborates with multiple departments to anticipate and address environmental issues by enhancing and innovating green practices.	
Complementary Knowledge Coupling (CKC)	CKC1	Our firm frequently integrates its internal technical management expertise with the complementary knowledge of collaborators.	Zhao et al. (2024)
	CKC2	Our firm fosters collaboration between different internal teams, merging diverse expertise across departments to improve processes and drive innovation.	
	CKC3	Our firm integrates internal and external knowledge to drive innovations and create new value propositions.	
	CKC4	Our firm consistently integrates insights from collaborative enterprises and internal teams to guide strategic operations and sustain competitive advantage.	
New Knowledge Diffusion (NKD)	NKD1	Our firm frequently shares operational insights among department members and their peers.	Chiu et al. (2024)
	NKD2	Our firm facilitates the exchange of technical expertise and practical know-how with external partners.	
	NKD3	Our firm promotes the sharing of business practices and experiential knowledge across departmental teams and their associates.	
	NKD4	Our firm has developed procedural guides for customer service and IT support operations.	

Construct	Item	Measurement Item	Source
Green Incremental Innovation (GII)	GII1	Our firm focuses on minor enhancements to its current eco-friendly products and services.	Zhou et al. (2023); Idrees et al. (2023)
	GII2	Our firm continually refines its environmentally sustainable operations.	
	GII3	Our firm frequently enhances existing processes to increase their environmental sustainability.	
	GII4	Our firm consistently exploits existing technologies to improve the environmental sustainability of its processes.	
	GII5	Our firm motivates employees to contribute fresh ideas that drive its eco-innovation efforts.	
	GII6	Our firm regularly upgrades and manages its production processes to reduce waste and lessen pollution risks.	
Green Radical Innovation (GRI)	GRI1	Our firm is at the forefront of developing groundbreaking, environmentally friendly techniques and technologies.	Idrees et al. (2023); Chen et al. (2014a)
	GRI2	Our company develops next-generation, environmentally friendly innovations in its products and services.	
	GRI3	Our firm dedicates investments to cutting-edge technologies to create novel green products.	
	GRI4	Our firm is dedicated to pioneering new experiences in green technology that did not exist previously.	
	GRI5	Our firm actively challenges existing environmental norms by introducing transformative green solutions that redefine industry standards.	
	GRI6	Our firm pursues environmental strategies that involve high uncertainty but have the potential to reshape	

Construct	Item	Measurement Item	Source
		sustainable practices significantly.	
Green Technology Turbulence (GTT)	GTT1	Eco-friendly technology across our sector is evolving rapidly.	Al-Swidi et al. (2023a); Aboalhool et al. (2024)
	GTT2	It is challenging to foresee the trajectory of green technology in our industry.	
	GTT3	A large portion of green innovations in our industry introduces significant departures from traditional techniques.	
	GTT4	Our industry's green technology landscape is marked by constant uncertainty, with frequent shifts and breakthroughs.	

Source: Adapted from Javed et al. (2025), Al-Swidi et al. (2024), Zhao et al. (2024), Chiu et al. (2024), Zhou et al. (2023), Idrees et al. (2023), Chen et al. (2014a), and Aboalhool et al. (2024).

Because all variables were collected from single respondents, common method bias (CMB) was assessed to ensure the validity and reliability of the constructs. CMB may occur when multiple constructs are measured simultaneously from the same source (Javed et al., 2024a). Harman's single-factor test was conducted, following Podsakoff et al. (2012). If a single factor explains more than 50% of total variance, substantial method bias may be present. In this study, the first factor explained only 21.9% of the total variance, indicating that CMB was not a serious concern.

The data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). This variance-based approach is appropriate for assessing complex models involving multiple observed and latent variables (Hair et al., 2020). SmartPLS was used to conduct the analysis because it provides a comprehensive platform for estimating PLS-SEM models and offers diagnostic tools for evaluating measurement and structural models. PLS-SEM was selected because it is suitable for testing direct, mediating, and moderating relationships in complex theoretical models such as the one proposed in this study.

4. Results

The measurement model was evaluated to ensure the reliability and validity of all constructs included in the study. Convergent validity was assessed using factor loadings and Average Variance Extracted (AVE). All indicator loadings exceeded the recommended threshold of 0.70, demonstrating satisfactory item reliability. Furthermore, all AVE values were greater than 0.50, indicating that each construct explained more than half of the variance of its indicators. Internal consistency reliability was confirmed through Cronbach's alpha and composite reliability values, which exceeded the recommended cutoff value of 0.70 for all constructs (Hair et al., 2019).

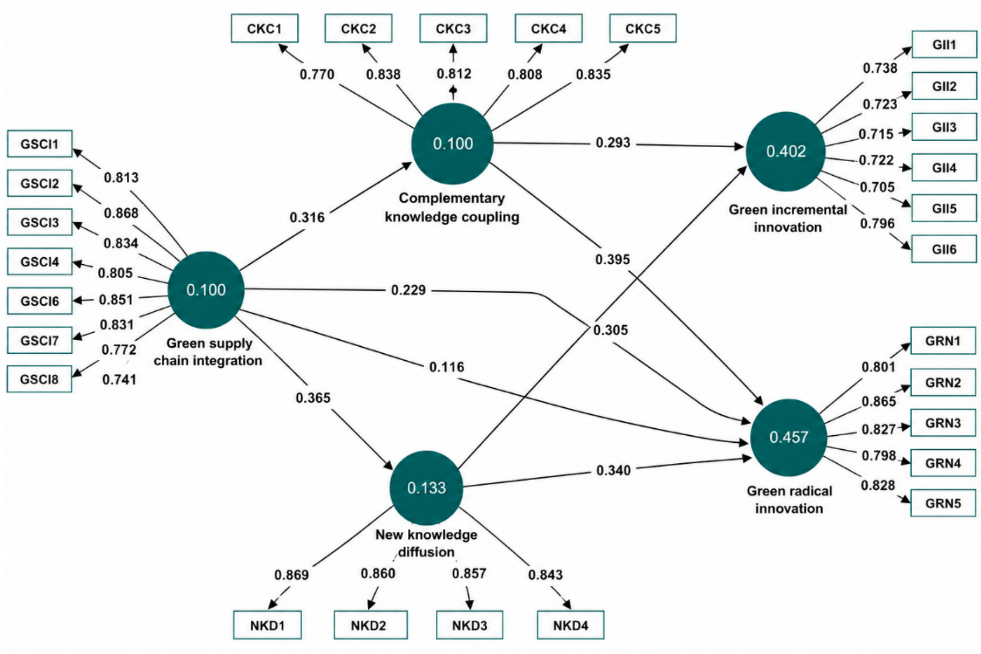

Figure 2. Measurement Model and Indicator Loadings

Table 3. Reliability and Convergent Validity Results

Construct	AVE	Factor Loading	Cronbach's Alpha	Composite Reliability
Green Supply Chain Integration (GSCI)	0.665		0.933	0.941
GSCI1		0.813		
GSCI2		0.868		
GSCI3		0.834		
GSCI4		0.805		
GSCI5		0.851		
GSCI6		0.831		
GSCI7		0.772		
GSCI8		0.741		
New Knowledge Diffusion (NKD)	0.735		0.880	0.917
NKD1		0.869		
NKD2		0.860		
NKD3		0.857		
NKD4		0.843		
Complementary Knowledge Coupling (CKC)	0.664		0.748	0.856
CKC1		0.770		
CKC2		0.838		
CKC5		0.835		
Green Incremental Innovation (GII)	0.514		0.812	0.864
GII1		0.738		
GII2		0.723		

Construct	AVE	Factor Loading	Cronbach's Alpha	Composite Reliability
GII3		0.715		
GII5		0.722		
GII6		0.705		
GII7		0.796		
Green Radical Innovation (GRI)	0.679		0.882	0.914
GRI1		0.801		
GRI2		0.865		
GRI3		0.827		
GRI4		0.798		
GRI5		0.828		

Discriminant validity was subsequently examined using the Fornell–Larcker criterion and the Heterotrait–Monotrait Ratio (HTMT). The square root of the AVE for each construct was higher than its correlations with other constructs, satisfying the Fornell–Larcker criterion. Additionally, all HTMT values were below the recommended threshold of 0.85, indicating adequate discriminant validity among the latent variables (Hair et al., 2021).

Table 4. Discriminant Validity Assessment using Fornell–Larcker and HTMT Criteria

Panel A. Fornell–Larcker Criterion

Construct	CKC	GII	GRI	GSCI	NKD
CKC	**0.815**				
GII	0.496	**0.717**			
GRI	0.577	0.525	**0.824**		
GSCI	0.316	0.434	0.365	**0.815**	
NKD	0.427	0.514	0.551	0.365	**0.857**

Panel B. HTMT Ratio

Construct	CKC	GII	GRI	GSCI	NKD
CKC	–				
GII	0.613	–			
GRI	0.694	0.610	–		
GSCI	0.367	0.488	0.393	–	
NKD	0.522	0.598	0.621	0.399	–

After confirming the adequacy of the measurement model, the structural model was evaluated using the bootstrapping procedure to test the proposed hypotheses. The results revealed that green supply chain integration (GSCI) had a significant positive effect on green incremental innovation (GII) ($\beta = 0.212$, $p < 0.001$) and green radical innovation (GRI) ($\beta = 0.153$, $p = 0.005$), thereby supporting H1 and H2. In addition, GSCI significantly enhanced complementary knowledge coupling (CKC) ($\beta = 0.316$, $p < 0.001$) and new knowledge diffusion (NKD) ($\beta = 0.365$, $p < 0.001$), confirming H3 and H4. The findings further indicated that CKC positively influenced both GII ($\beta = 0.294$, $p < 0.001$) and GRI ($\beta = 0.390$, $p < 0.001$), supporting H5 and H6. Similarly, NKD exerted significant positive effects on GII ($\beta = 0.330$, $p < 0.001$) and GRI ($\beta = 0.271$, $p < 0.001$), thereby supporting H7 and H8.

Table 5. Direct Effects and Hypothesis Testing Results

Hypothesis	Relationship	β	STDEV	t-value	p-value	Result
H1	GSCI → GII	0.212	0.055	3.832	0.000	Accepted
H2	GSCI → GRI	0.153	0.054	2.838	0.005	Accepted
H3	GSCI → CKC	0.316	0.053	5.992	0.000	Accepted
H4	GSCI → NKD	0.365	0.049	7.376	0.000	Accepted
H5	CKC → GII	0.294	0.052	5.640	0.000	Accepted
H6	CKC → GRI	0.390	0.053	7.409	0.000	Accepted
H7	NKD → GII	0.330	0.066	5.015	0.000	Accepted
H8	NKD → GRI	0.271	0.056	4.846	0.000	Accepted

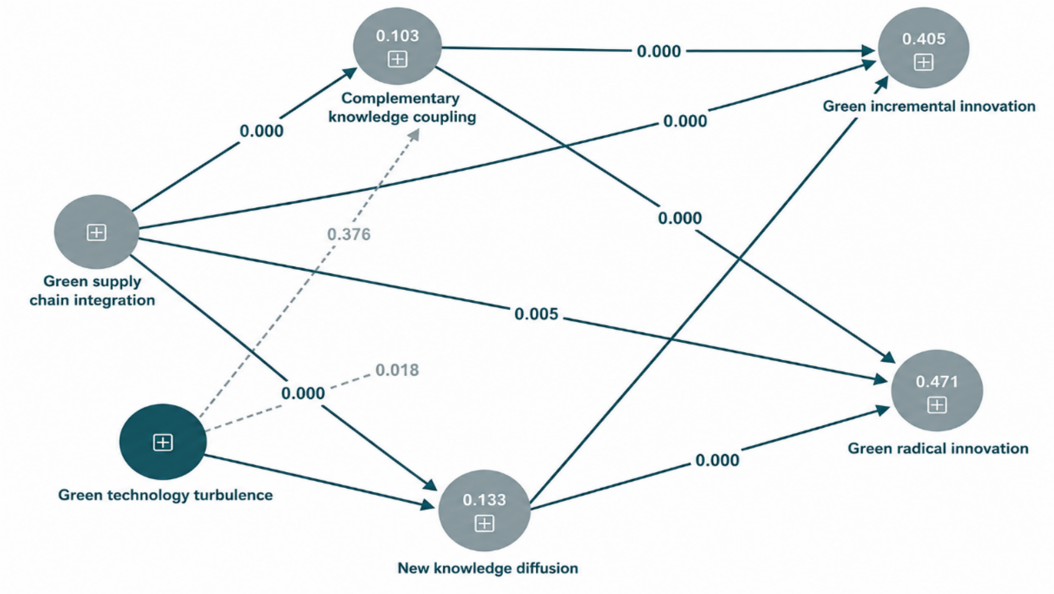

Figure 3. Structural Model Results

The mediating effects of CKC and NKD were then examined. The results demonstrated that CKC significantly mediated the relationship between GSCI and GII ($\beta = 0.093$, $p < 0.001$) as well as the relationship between GSCI and GRI ($\beta = 0.123$, $p < 0.001$). Likewise, NKD significantly mediated the influence of GSCI on GII ($\beta = 0.120$, $p < 0.001$) and GRI ($\beta = 0.099$, $p < 0.001$). These findings confirm that both knowledge-related capabilities serve as important mechanisms through which green supply chain integration enhances green innovation outcomes.

Table 6. Mediation Analysis Results

Hypothesis	β	STDEV	t-value	p-value	Result
GSCI → CKC → GII	0.093	0.023	3.997	0.000	Accepted
GSCI → CKC → GRI	0.123	0.030	4.068	0.000	Accepted
GSCI → NKD → GII	0.120	0.028	4.372	0.000	Accepted
GSCI → NKD → GRI	0.099	0.024	4.129	0.000	Accepted

Finally, the moderating role of green technology turbulence (GTT) was assessed. The analysis revealed that GTT significantly strengthened the relationship between GSCI and GRI ($\beta = 0.097$, $p = 0.018$), suggesting that higher levels of technological turbulence enhance the effectiveness of supply chain integration in promoting radical green innovation. However, the interaction effect between GSCI and GTT on GII was not significant (β = −0.046, p = 0.376), indicating that technological turbulence does not substantially influence the relationship between GSCI and incremental green innovation.

Table 7. Moderation Analysis Results

Hypothesis	β	STDEV	t-value	p-value	Result
GSCI × GTT → GII	-0.046	0.052	0.886	0.376	Not Accepted
GSCI × GTT → GRI	0.097	0.041	2.375	0.018	Accepted

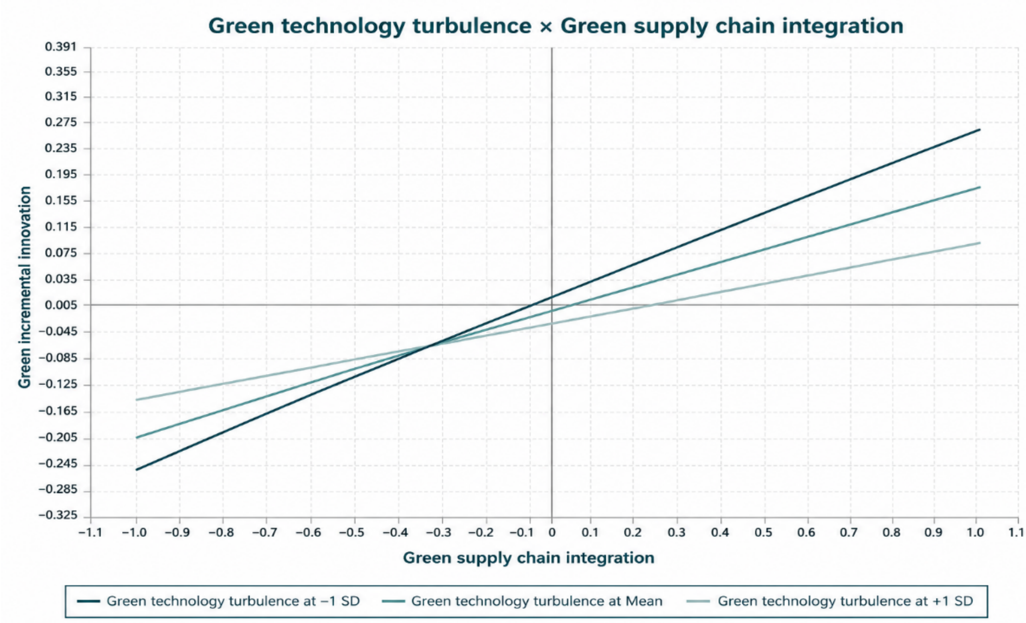

Figure 4. Moderating Effect of Green Technology Turbulence on the Relationship between GSCI and Green Radical Innovation

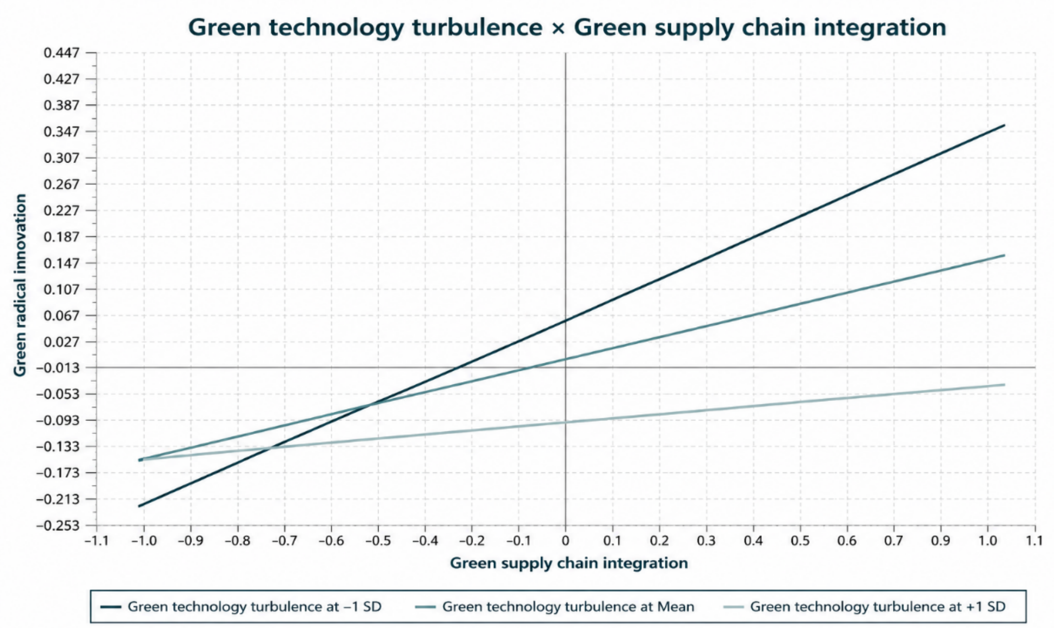

Figure 5. Moderating Effect of Green Technology Turbulence on the Relationship between GSCI and Green Incremental Innovation

5. Discussion

This study examines the role of green supply chain integration (GSCI) in promoting green incremental innovation (GII) and green radical innovation (GRI) by incorporating complementary knowledge coupling (CKC), new knowledge diffusion (NND), and green technology turbulence (GTT) within the frameworks of Knowledge-Based View (KBV) and Contingency Theory (CT). The findings demonstrate that GSCI significantly enhances both GII and GRI, indicating that stronger collaboration and integration with supply chain partners facilitate the acquisition, sharing, and utilization of environmental knowledge required for innovation. The effect of GSCI is more pronounced on GII than on GRI, suggesting that integrated supply chain relationships are particularly effective in supporting continuous improvements to existing products and processes. In contrast, radical innovation requires more complex knowledge recombination, higher investment, and greater tolerance for uncertainty, making its development comparatively more challenging.

The results further reveal that CKC plays a significant mediating role in the relationship between GSCI and both forms of green innovation. By integrating internal expertise with external knowledge acquired from supply chain partners, firms can strengthen their innovation capabilities and generate more sustainable solutions. These findings support the KBV perspective, which emphasizes knowledge as a strategic resource that drives organizational competitiveness and innovation. Similarly, NND significantly mediates the influence of GSCI on GII and GRI. Effective knowledge diffusion enables firms to rapidly disseminate and absorb valuable information across organizational boundaries, facilitating both the refinement of existing green practices and the development of transformative environmental innovations. Together, CKC and NND act as critical mechanisms through which supply chain integration is translated into innovation outcomes.

Regarding the moderating role of environmental conditions, the findings indicate that GTT does not significantly influence the relationship between GSCI and GII. Incremental innovation is generally rooted in established routines, accumulated experience, and existing organizational capabilities, making it less sensitive to technological turbulence. Conversely, GTT significantly strengthens the relationship between GSCI and GRI. In highly dynamic technological environments, firms are compelled to seek new knowledge, adopt advanced technologies, and collaborate more intensively with supply chain partners to remain competitive. As a result, technological turbulence amplifies the effectiveness of GSCI in fostering radical green innovation. This finding supports the central proposition of Contingency Theory that organizational effectiveness depends on the alignment between internal capabilities and external environmental conditions.

From a theoretical perspective, this study extends the literature on green supply chain management and green innovation by simultaneously examining incremental and radical innovation outcomes. The findings enrich the KBV by demonstrating that knowledge coupling and knowledge diffusion serve as essential pathways through which integrated supply chain relationships generate innovation. Furthermore, the study advances Contingency Theory by showing that environmental turbulence affects different types of innovation in distinct ways, highlighting important boundary conditions in the GSCI–innovation relationship. The study also contributes to the limited empirical evidence from emerging economies, particularly Pakistan, where institutional constraints, fragmented supply chains, and evolving environmental regulations create unique conditions for green innovation.

The findings also offer several managerial and policy implications. Managers should strengthen collaboration with suppliers, customers, and internal departments to facilitate knowledge exchange and improve innovation performance. Developing mechanisms that support complementary knowledge coupling and effective knowledge diffusion can help organizations transform dispersed knowledge into valuable innovation outcomes. Firms should also invest in digital platforms, cross-functional collaboration, and knowledge-sharing systems to accelerate both incremental and radical innovation. Policymakers can support these efforts by promoting collaborative innovation networks, encouraging green technology adoption, and providing incentives for environmentally sustainable business practices. Such initiatives can enhance organizational resilience, improve environmental performance, and contribute to broader sustainability objectives, particularly in emerging economies facing increasing ecological and competitive pressures.

6. Conclusions

This study investigates the influence of green supply chain integration (GSCI) on green incremental innovation (GII) and green radical innovation (GRI) by incorporating complementary knowledge coupling (CKC), new knowledge diffusion (NND), and green technology turbulence (GTT) within the frameworks of Knowledge-Based View (KBV) and Contingency Theory (CT). The findings demonstrate that GSCI positively enhances both GII and GRI, confirming that stronger collaboration and integration among supply chain partners facilitate the acquisition, integration, and utilization of environmental knowledge required for sustainable innovation. Furthermore, CKC and NND were found to significantly mediate the relationship between GSCI and both forms of green innovation, highlighting the importance of knowledge integration and knowledge dissemination as key mechanisms through which supply chain integration generates innovation outcomes. The results also reveal that green technology turbulence strengthens the effect of GSCI on green radical innovation but does not significantly influence green incremental innovation, indicating that environmental uncertainty is more relevant for transformative innovation activities than for continuous improvement initiatives.

The study contributes to the growing literature on green innovation by providing empirical evidence that knowledge-based capabilities and supply chain integration jointly support sustainable innovation performance. In particular, the findings emphasize that organizations can achieve stronger green innovation outcomes when they effectively combine internal and external knowledge resources and facilitate the diffusion of new knowledge throughout the organization. From a managerial perspective, the results suggest that firms should strengthen collaborative relationships with suppliers and customers, invest in knowledge-sharing mechanisms, and develop adaptive capabilities that enable them to respond to rapidly changing technological environments. Policymakers can further support these efforts by promoting collaborative green innovation networks, encouraging environmentally sustainable practices, and facilitating access to green technologies.

Despite its contributions, this study has several limitations that provide opportunities for future research. First, the study relies on cross-sectional data and focuses primarily on large manufacturing firms operating in a developing economy context. Future research may adopt longitudinal research designs to examine how the relationships among GSCI, CKC, NND, and green innovation evolve over time and to provide stronger causal evidence. Second, future studies should conduct cross-country and cross-cultural comparisons involving developed, developing, and less-developed economies to assess the generalizability of the findings under different institutional and cultural environments. Third, GSCI was operationalized as a single construct in this study; therefore, future research should distinguish between supplier integration, customer integration, and internal integration to identify their unique contributions to different forms of green innovation. Fourth, additional studies could explore how market-oriented policies and regulatory mechanisms reduce environmental uncertainty and encourage sustainable innovation practices. Finally, given that green technology turbulence significantly influenced radical innovation but not incremental innovation, future research should investigate organizational mechanisms such as inertia, exploitative routines, organizational stability, and absorptive capacity that may explain why incremental innovation remains relatively insulated from external technological disruptions.

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