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Influence of Supply Chain Ambidexterity on Supply Chain Sustainability: The Mediating Role of Green Product Innovation

Luay Jum'a [1], Ahmed Adnan Zaid [2,3,*] and Mohammed Othman [4]

[1] Department of Logistics Sciences, Business School, German Jordanian University, Amman 11180, Jordan; luay.juma@gju.edu.jo
[2] Department of Management, The College of Economics, Management and Information Systems, University of Nizwa, Nizwa 616, Oman
[3] Department of Logistic Management, Faculty of Business and Economics, Palestine Technical University—Kadoorie, Tulkarm P.O. Box 7, Palestine
[4] Department of Industrial and Mechanical Engineering, Faculty of Engineering, An-Najah National University, Nablus 7, Palestine; m_othman@najah.edu
* Correspondence: a.zaid@ptuk.edu.ps

Abstract

Background: This study conceptualizes supply chain ambidexterity through two capabilities, supply chain adaptability and agility. Accordingly, it investigates the impact of supply chain adaptability and agility on green product innovation (GPI) and supply chain sustainability in Jordanian manufacturing firms. It also examines the mediating role of GPI in these relationships. The study is based on dynamic capabilities theory (DCT) as the theoretical foundation. *Methods*: A quantitative research approach was employed, with data collected from 346 supply chain managers using a structured questionnaire. Partial Least Squares Structural Equation Modeling (PLS-SEM) was used for analysis. *Results*: The findings reveal that supply chain adaptability does not directly influence sustainability but significantly enhances GPI, which positively impacts sustainability. Supply chain agility, however, directly and significantly improves both GPI and sustainability, highlighting its importance in achieving sustainable supply chain performance. Additionally, GPI mediates the relationship between supply chain ambidexterity and sustainability, reinforcing its role as a key enabler of eco-friendly supply chain management. These findings provide theoretical and managerial implications. *Conclusions*: The study extends DCT by confirming the role of GPI in linking supply chain ambidexterity to sustainability. Managers should prioritize agility, invest in sustainable products, and adopt green practices to enhance competitiveness.

Keywords: supply chain ambidexterity; supply chain adaptability; supply chain agility; supply chain sustainability; green product innovation; manufacturing firms

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1. Introduction

Environmental concerns have increasingly driven governments and regulatory bodies to impose stricter policies aimed at minimizing harmful industrial practices [1]. Many businesses have been compelled to reconsider their operations due to the negative consequences of unsustainable practices, including pollution, depletion of natural resources, shrinking green spaces, and rising industrial waste [2]. Companies that want to be competitive and socially conscious need to find the balance between supply chain sustainability and economic success by including green product innovation (GPI) in their corporate plans [3].

To achieve supply chain sustainability, firms need to mitigate environmental impact while concurrently enhancing productivity, corporate reputation, and market positioning. This is fundamentally reliant on GPI and supply chain ambidexterity, which integrates exploratory (adaptability) and exploitative (agility) strategies [4]. This dual capacity reflects supply chain ambidexterity, where organizations deliberately balance flexibility-oriented activities (adaptability/exploration) with efficiency-oriented activities (agility/exploitation) to sustain competitive advantage [5,6].

Supply chain ambidexterity refers to the simultaneous pursuit of supply chain exploitation (agility) that is focused on efficiency as well as exploration (adaptability) that is focused on flexibility, by integrating adaptability and agility within supply chain management [7,8]. Traditional thinking suggests that companies must choose between adaptable supply chains for innovative products and efficient supply chains for functional products [9]. However, supply chain ambidexterity provides a strategic approach that integrates adaptability and agility, enabling companies to address evolving market demands while maintaining operational excellence [10]. Within this framework, supply chain adaptability and agility emerge as primary catalysts for GPI and supply chain sustainability [8,11]. Numerous studies indicate that these capabilities (adaptability and agility) facilitate the adoption of new innovations such as GPI and supply chain sustainable performance, thereby enhancing corporate resilience and long-term performance [4–6,12,13].

The trend of connecting GPI with supply chain sustainability stems from the practices of green supply chain management (GSCM). GSCM has gained significance as companies face mounting pressure to integrate sustainable practices and address environmental concerns within their supply chain operations [14]. This connection can be reinforced through supply chain ambidexterity, which enables firms to balance adaptability and agility enhancing their capacity to achieve operational efficiency while advancing environmental sustainability, thereby supporting the adoption of supply chain sustainability [15].

Supply chain agility enables companies to accurately align supply with demand, thereby reducing storage and transportation expenses and facilitating rapid responses to market fluctuations [9]. Reducing lead times, improving production flexibility, and customizing product offerings would assist companies in minimizing unnecessary inventory buildup and preventing price reductions caused by surplus inventory [16]. Similarly, supply chain adaptability enables companies to diversify their supplier networks, explore new markets, and establish alternative production capacities, while supply chain flexibility ensures consistent quality and dependable delivery amid economic and market disruptions [17]. The combination of supply chain agility and adaptability enhances supply chain resilience and efficiency, thereby promoting supply chain sustainability performance [10,18]. While GPI is recognized as a primary catalyst for supply chain sustainability, its role as a mediator between supply chain ambidexterity and sustainable performance remains insufficiently explored in the literature [3,19,20].

GPI involves creating eco-friendly products using sustainable materials, energy-efficient manufacturing processes, and environmentally conscious design. Integrating GPI into supply chain operations not only enhances environmental sustainability but also supports firms in maintaining competitive advantage. However, the specific mechanisms by which supply chain agility and supply chain adaptability (the two core dimensions of supply chain ambidexterity) influence GPI and, in turn, supply chain sustainability remain underexplored [5,21]. While previous studies have examined the individual impacts of supply chain ambidexterity on either GPI or supply chain sustainability, few studies have empirically investigated the mediating role of GPI in these relationships.

For instance, while Cancela et al. [5] as well as Kara and Edinsel [21] highlight how green innovation, including GPI, enhances environmental performance, they do not posi-

tion GPI as a mediator between supply chain capabilities and sustainability. Similarly, Sun and Sun [4] acknowledge the potential of green supply chain integration in enabling ambidextrous innovation yet stop short of examining GPI as an explicit mediating mechanism. This underscores a critical gap in the literature: the lack of integrated models that explain how supply chain agility and adaptability (supply chain ambidexterity), as dynamic capabilities, enable supply chain sustainability through GPI. To address this gap, the present study contributes by empirically validating GPI as a mediating variable, thereby enriching the theoretical understanding and practical application of supply chain ambidexterity in sustainable supply chain management.

Based on dynamic capabilities theory (DCT), which holds that companies have to constantly adapt, combine, and reorganize their resources to keep a competitive advantage in evolving surroundings [22], this study is grounded. DCT defines supply chain agility and adaptability as dynamic skills that enable companies to exploit fresh opportunities and meet environmental problems. Using these features can help companies promote GPI, therefore improving the performance of sustainability. Research on the mediating function of GPI in the link between supply chain ambidexterity and sustainability is still lacking even if sustainability-oriented supply chain activities are becoming more and more interesting [5,21].

This study focuses on supply chain adaptability and agility embedded within manufacturing firms in Jordan, where GPI is primarily driven by internal production capabilities. However, these innovations are often enabled and sustained through coordination across the supply chain, including supplier collaboration, sustainable procurement, and reverse logistics [4,5,21]. As such, while manufacturing operations initiate and implement GPI, the effectiveness and scalability of these efforts depend on the dynamic capabilities, namely adaptability and agility, of the wider supply chain network [13,19]. This framing positions our analysis within the context of manufacturing-based supply chains, where the interplay between internal innovation and external coordination shapes supply chain sustainability. With GPI as a mediator, this study looks at how supply chain agility and adaptability affect supply chain sustainability to close this disparity. This work offers a fresh viewpoint on the interaction among sustainability, agility, and adaptability by including DCT in supply chain ambidexterity research. The results will support theory and practice by providing an understanding of how companies could strategically apply GPI as a means of improving the performance of their sustainable supply chains.

Thus, this study contributes to the literature of supply chain sustainability in several important ways. Theoretically, it advances the application of DCT by empirically distinguishing between supply chain adaptability and agility as discrete dynamic capabilities and examining their differentiated roles in enabling GPI and sustainability performance, which is an area that remains underexplored in prior research [5,21,22]. By positioning GPI as a mediating mechanism, the study enhances understanding of how dynamic capabilities translate into sustainable outcomes, thus filling a gap in the existing supply chain ambidexterity literature [3,19,20].

Practically, the study offers actionable insights into manufacturing firms in Jordan, which is a context that has received limited attention by identifying agility as a more immediate driver of sustainability and highlighting the importance of embedding green innovation into supply chain strategies to meet growing regulatory and consumer demands [2,13,15]. Methodologically, the study employs Partial Least Squares Structural Equation Modeling (PLS-SEM) using data from 346 supply chain professionals across Jordanian manufacturing firms, providing robust empirical evidence from a developing country context and enriching the global discourse on sustainable supply chain management in emerging economies.

The rest of the paper is divided as follows: Section 2 summarizes earlier studies on supply chain ambidexterity, GPI, and sustainability; Section 3 describes the conceptual model and hypotheses formulation; Section 4 describes the methods of research including approaches of data collecting and analysis; Section 5 addresses the findings; Section 6 offers theoretical and managerial ramifications together with study constraints and future areas for research.

2. Literature Review

2.1. Green Innovation, Supply Chain Ambidexterity, and Sustainability

As companies seek to strengthen their competitive advantage through unique capabilities and innovations such as GPI, the concept of ambidexterity has gained increasing attention in supply chain management. Ambidextrous firms balance adaptability, which supports innovation and responsiveness to evolving market conditions, and agility, which ensures operational efficiency and quick reactions to short-term disruptions. Adaptability, in particular, enables firms to sense, interpret, and respond proactively to shifting environmental challenges and changing customer demands [13]. Much research on various aspects of supply chain ambidexterity (adaptability and agility) have shown how important it is for promoting innovation, sustainability, and long-term corporate performance [12–16].

Strong correlation between supply chain ambidexterity and GPI has already been demonstrated by earlier studies, particularly while consumer pressure is great. Cancella et al. [5] showed that ambidexterity improves sustainability and increases the success of GPI. Though networking capabilities do not modify this association, Khan et al. [15] also observed that supply chain ambidexterity improves GSCM. Chan et al. [19] investigated further how green product development affects company performance and found that sustainability-oriented innovations driven by regulatory pressures increase operational efficiency and profitability by themselves.

Beyond its direct impact on GPI, supply chain ambidexterity has also been related to supply chain performance. While ambidextrous supply chains do not directly improve supply chain performance, Alamsjah and Asrol [23] discovered that they indirectly support agility and lean supply chains by means of which they contribute. Likewise, Rojo et al. [24] found that ambidextrous supply chains increase supply chain flexibility, hence improving general corporate performance. According to Jermsittiparsert and Pithuk [13], supply chain ambidexterity favorably correlates with adaptability and agility, both of which enhance companies' market response and operational efficiency.

Many studies have underlined the mediation role played by green supply chain policies in the link between ambidexterity and sustainability. Sun and Sun [4] underlined how green supply chain integration helps ambidextrous green innovation, thereby improving both exploratory and exploitative output of innovation. With organizational ambidexterity serving as a mediator, Al-khawaldah et al. [2] also showed that GSCM including sustainable sourcing, manufacturing, and marketing greatly adds to competitive advantage. The link between green supply chain practices, including GPI and competitive advantage, has been empirically supported in several studies. For instance, Al-Khawaldah et al. [2] demonstrated that firms engaging in sustainable sourcing, green manufacturing, and eco-conscious marketing observed improvements in market positioning and cost efficiency, which are both key indicators of competitive advantage. Similarly, Khan et al. [15] found that supply chain ambidexterity enhances the firm's ability to respond to environmental demands while maintaining operational efficiency, thereby strengthening differentiation and customer loyalty. These findings suggest that the integration of green innovation and dynamic supply chain capabilities not only improves sustainability outcomes but also leads to measurable competitive benefits such as increased customer satisfaction, enhanced

brand image, and reduced operational risk [4,13,21]. Emphasizing the need for internal skills in advancing sustainability, Kara and Edinsel [21] demonstrated that GPI moderates the link between green human resource management (GHRM) and GSCM.

Also evolving are the theoretical viewpoints on supply chain ambidexterity and sustainability [8]. Using resource dependency theory, Sun and Sun [4] sought to explain how companies create ambidextrous green innovation strategies in reaction to outside demand. Rintala et al. [25] connected ambidexterity in logistics to the connection of economic and environmental sustainability, proving that companies with great exploratory capacities produce better environmental and financial results. With governance ambidexterity influencing second-order social capital, Zhao et al. [26] investigated from a social exchange and transaction cost standpoint how this influences green innovation. Emphasizing the strategic importance of leadership and institutional support, Aftab et al. [27] also looked at the mediating function of entrepreneurial orientation in tying ambidexterity to sustainability and company performance.

More recently, Belhadi et al. [28] similarly examined the interaction between ambidexterity, circular business models, and digital transformation to demonstrate how ambidexterity might replace circular economy approaches in promoting sustainable performance. With ambidextrous management serving as a moderator, Zhang et al. [29] expanded this conversation by examining how green supplier integration improves environmental performance through green product and process innovation, such as the development of eco-friendly materials, energy-efficient production methods, and waste-reducing manufacturing practices.

To address the distinction between firm-level and supply chain level innovation, it is important to note that while prior studies have demonstrated the impact of organizational ambidexterity on GPI and sustainability within individual manufacturing firms [5,15,19], fewer have extended this examination to the broader supply chain context. Most existing research focuses on firms that directly produce green products; however, in practice, green product innovation is increasingly a collaborative effort across supply chain partners, involving joint design, sustainable sourcing, logistics coordination, and end-of-life recycling strategies [4,21]. By conceptualizing ambidexterity at the supply chain level, this study examines how supply chain adaptability (long-term structural reconfiguration) and agility (short-term responsiveness) enable green innovation through cross-functional and inter-organizational mechanisms. This approach aligns with the view that sustainability outcomes depend not only on internal capabilities, but also on the dynamic coordination and innovation capacity of the entire supply chain network [13,28].

Despite these advancements, the literature still exhibits particular deficiencies. While prior studies have demonstrated that supply chain ambidexterity fosters green innovation and sustainability, the specific mechanisms through which supply chain adaptability and agility facilitate sustainable supply chains remain inadequately explored [6,8]. Moreover, while GPI is recognized as a significant factor in sustainability, its function as an intermediary between supply chain ambidexterity and supply chain sustainability has received minimal empirical scrutiny [5,15,19].

While GPI is often viewed as the outcome of firm-level R&D or product design efforts, recent studies increasingly conceptualize GPI as a supply chain-enabled process involving upstream and downstream collaboration across supply chain partners [4,21]. This includes activities such as co-design with suppliers, integration of eco-friendly raw materials, green procurement, and reverse logistics demonstrating that GPI extends beyond product development into operational and relational supply chain functions [19,29]. Therefore, treating GPI as a supply chain level construct is both theoretically grounded and practically relevant, as the capacity to innovate green products often depends on the dynamic capabilities of the

entire supply chain network, not just the manufacturer. This broader view supports the argument that supply chain ambidexterity—particularly in terms of flexibility, responsiveness, and knowledge sharing—can play a foundational role in enabling GPI, which in turn contributes to sustainability outcomes [5,13,28].

To ensure conceptual alignment with our empirical design, it is important to emphasize that this study applies DCT to examine how supply chain-related capabilities function within manufacturing firms, rather than across full, multi-tier supply chains. While the term "supply chain ambidexterity" is used, the dynamic capabilities under investigation (adaptability and agility) refer to intra-firm capabilities that influence how a manufacturing firm manages its upstream and downstream interactions to support GPI [5,10,13]. This framing is consistent with prior studies that operationalize supply chain constructs through the perspective of focal firms, particularly in developing country contexts where firm-level capacity building plays a central role in sustainable supply chain management [19,21,29]. As such, our theoretical framework is grounded in how firm-internal supply chain capabilities drive innovation and sustainability outcomes, and not in an analysis of the entire supply chain network.

Synthesis of Literature on Ambidexterity, Green Product Innovation, and Supply Chain Sustainability

The previous section presents a critical synthesis of the literature on GPI, supply chain ambidexterity, and sustainability, progressing from broader theoretical underpinnings to specific research gaps. The section begins by defining organizational ambidexterity as a balance between exploration and exploitation (adaptability and agility) and examines how this dynamic capability particularly adaptability and agility supports both innovation and long-term performance in supply chains [12–16]. Studies such as Cancela et al. [5] and Khan et al. [15] show that ambidexterity strengthens GSCM and enhances GPI, especially under stakeholder and regulatory pressures [19]. However, much of this research focuses on individual firms rather than supply chains as inter-organizational systems. Later studies (e.g., Rojo et al. [24], Alamsjah and Asrol [23]) extend this view by linking ambidexterity to supply chain flexibility and resilience, though often without examining the mechanisms by which dynamic capabilities translate into sustainability outcomes. Some contributions, like Sun and Sun [4] as well as Kara and Edinsel [21], identify GPI as a moderator or mediator in broader sustainability strategies, yet do not empirically test its intermediary role between ambidexterity and sustainable supply chain performance. The literature also introduces evolving theoretical lenses such as resource dependence theory [4], social exchange theory [26], and digital transformation [28] that expand ambidexterity's conceptual scope, though not always directly aligned with supply chain level innovation.

This section identifies a key gap: while DCT provides a compelling framework for understanding dynamic capabilities, few studies empirically test how adaptability and agility, as distinct intra-firm supply chain capabilities, contribute to GPI and sustainability within manufacturing contexts [6,8]. Moreover, the role of GPI as a mediating construct remains underexplored and conceptually vague in many prior works [5,15,19]. Given the increasing recognition of GPI as a supply chain-enabled process involving supplier collaboration, eco-design, and reverse logistics [4,21,29], this study builds on the existing literature by situating ambidexterity within firm-level supply chain functions in manufacturing firms—particularly in a developing country context. It advances theory by proposing and testing a model that conceptualizes GPI as the link through which agility and adaptability drive sustainable outcomes, thereby addressing both theoretical and empirical gaps.

Therefore, this study aims to investigate the influence of supply chain adaptability and agility on sustainable supply chains, with GPI acting as a mediator. This research formulates a theoretical framework for understanding how organizations restructure their

supply chain capabilities to achieve sustainability via the integration of DCT. This research integrates supply chain adaptability and agility, offering a more refined perspective on how organizations tackle sustainability issues, unlike other studies that focus on general ambidexterity. Table 1 delineates the primary previous studies in the field.

Table 1. Summary of past studies in the domain.

Study	Independent Variables	Dependent Variables	Other Variables (Mediating/ Moderating)
Ahmad and Khokhar [8]	Sustainable supply chain management (SSCM) practices	Sustainability performance	Supply chain ambidexterity
Stei et al. [6]	Organizational ambidexterity (Exploration and exploitation)	Organizational agility and performance	Environmental competitiveness (a firm's ability to gain a competitive advantage through environmentally sustainable practices)
Cancela et al. [5]	Ambidexterity (Exploration and exploitation)	GPI, business performance	Consumer pressure
Kara and Edinsel [21]	GHRM	GSCM	GPI
Aftab et al. [27]	Ambidexterity in organizations	Company's successful financial performance, environmental sustainability	Entrepreneurial mindset
Alamsjah and Yunus [12]	Supply chain ambidexterity	SC 4.0 Maturity (the extent to which a company has adopted Industry 4.0 technologies within its supply chain operations)	Supply chain agility
Alamsjah and Asrol [23]	Supply chain ambidexterity	Supply chain performance	Agile and lean supply chain
Al-khawaldah et al. [2]	Green supply chain practices	Competitive advantage	Organizational ambidexterity
Belhadi et al. [28]	Organizational ambidexterity and Industry 4.0 capabilities	Sustainable performance	Digital business transformation, circular business models
Rintala et al. [25]	Ambidexterity	Economic and environmental sustainability	Exploratory orientation (Refers to a firm's strategic focus on experimentation, risk-taking, and the pursuit of novel opportunities)
Khan et al. [15]	Ambidextrous supply chain	GSCM	Networking capabilities (Denote a firm's ability to build, manage, and leverage relationships with external partners such as suppliers and customers)
Sun and Sun [4]	Ambidextrous green innovation	Green innovation strategy	Green supply chain integration
Zhang et al. [29]	Green supplier integration	Environmental performance	Ambidextrous management
Jermsittiparsert and Pithuk [13]	Supply chain ambidexterity, agility, adaptability	Market sensing (Involves the firm's capacity to detect, interpret, and respond to emerging market trends, customer needs, and competitive dynamics)	Agility, adaptability

Table 1 presents a structured summary of selected empirical studies that explore the relationships among supply chain ambidexterity, GPI, and supply chain sustainability. The studies were selected based on their relevance to the three core constructs of this research namely adaptability, agility, and green product innovation and their empirical focus on manufacturing or supply chain contexts. Care was taken to include only peer-reviewed studies published in the last 10 years. To ensure clarity and comparability, all listed variables have been standardized according to established terminology in the literature. This table not only highlights consistent findings across contexts but also underscores the lack of studies that empirically test GPI as a mediator between supply chain capabilities and sustainability—thereby reinforcing the theoretical gap this study seeks to address [4,21,29].

2.2. Hypotheses of the Conceptual Framework

While both supply chain adaptability and agility are categorized as dynamic capabilities, they operate on different temporal and strategic dimensions [8,13]. Adaptability refers to a firm's ability to undertake long-term structural changes, such as reconfiguring supplier networks, relocating production facilities, or adopting new technologies to cope with persistent shifts in the market or regulatory environment [10,17]. It is proactive and strategic in nature, focusing on building resilience over time. In contrast, agility involves short-term operational responsiveness, enabling firms to react quickly to unexpected disruptions, fluctuating demand, or supply uncertainties by adjusting production, logistics, or sourcing strategies [11,18]. Agility is tactical and execution-focused, facilitating immediate adjustments to maintain service levels and minimize costs. Clarifying this distinction ensures a more accurate understanding of how each capability uniquely contributes to green product innovation (GPI) and supply chain sustainability [4,12].

Moreover, to strengthen the theoretical foundation, clarification is needed on how DCT supports the development of the research hypotheses before discussing them in detail. DCT provides a robust theoretical foundation for examining how organizations respond to changing environmental conditions by continuously integrating, reconfiguring, and renewing their internal and external competencies [22]. Within this framework, supply chain adaptability and agility are viewed as dynamic capabilities that enable firms to sense opportunities, seize them through timely action, and reconfigure operations to maintain competitiveness and sustainability [10,13]. Adaptability supports long-term strategic changes, such as supplier network reconfiguration and technology adoption, while agility enables rapid operational responses to fluctuating market and regulatory demands [17,18]. These capabilities do not guarantee sustainable outcomes unless directed toward innovation. GPI serves as the operational mechanism that translates these dynamic capabilities into sustainability performance by embedding eco-efficiency and environmental compliance into the firm's offerings [4,19]. Thus, the research model is grounded in DCT by conceptualizing agility and adaptability as enablers, GPI as a capability deployment mechanism, and sustainability as the performance outcome.

2.2.1. Impact of Supply Chain Adaptability

Supply chain adaptability refers to a company's ability to recognize significant, lasting changes in the supply chain and markets such as economic variations, political and social changes, demographic transitions, and technological advancements and to restructure its supply network accordingly. This may involve establishing new supplier networks, relocating manufacturing operations, or outsourcing critical processes [17]. The ability to identify and swiftly respond to evolving market conditions is a crucial skill that heavily relies on adaptability [13].

SSCM denotes the coordination of material, information, and financial flows among supply chain partners, considering the three pillars of sustainability—economic, environmental, and social—in alignment with customer and stakeholder requirements [22]. In this context, adaptability is crucial for organizations to integrate sustainability factors into their supply chains while maintaining operational efficiency [30]. The ability to absorb and apply external knowledge is essential for fostering innovation and sustainability [22]. Shan et al. [31] found that absorptive capacity significantly influences the relationship between organizational structure and collaborative creativity, highlighting the importance of organizations' capability to integrate external knowledge into their innovation processes.

Furthermore, network competencies, defined by the ability to establish, maintain, and leverage relationships with various external partners, are crucial for effective supply chain management. Khan et al. [15] found that while network competencies are essential for managing sustainable supply chains, they do not inherently affect the relationship between supply chain flexibility and GSCM. This signifies that adaptability is an essential element in the success of green supply chains, regardless of networking capabilities.

Supply chain adaptability enables firms to reconfigure internal operations and external partnerships in response to long-term market or regulatory shifts, thereby enhancing their capacity to integrate sustainable inputs and redesign processes toward greener outputs [10,13]. By fostering absorptive capacity and strategic reorientation, adaptability serves as a foundation for building innovation readiness in volatile environments [22,31]. Alamsjah and Asrol [23] emphasized the importance of dynamic skills in responding to technological and consumer-driven changes, particularly in high-risk supply chain environments such as inter-island logistics. They highlighted that firms with strong resource capabilities and execution proficiency are more skilled at navigating environmental uncertainties. Adaptability, as a dynamic competency, enables organizations to restructure their supply chains in the long term, ensuring resilience and sustainability amid market disruptions.

Grounded in DCT, supply chain adaptability represents a firm's ability to realign and reconfigure its supply chain structure, relationships, and processes in response to long-term changes in the external environment [22]. This includes responding to shifts in regulatory requirements, consumer preferences for environmentally friendly products, and resource scarcity by modifying sourcing strategies, redesigning logistics systems, or integrating cleaner technologies [13,30]. Adaptability enables firms to proactively engage with sustainability goals by institutionalizing environmental standards across the supply chain, thereby going beyond compliance toward continuous improvement in sustainability performance [17,31]. Unlike agility, which addresses immediate disruptions, adaptability facilitates structural change that aligns organizational processes with long-term environmental and social objectives [10,18]. Therefore, as a dynamic capability, adaptability plays a strategic role in enhancing supply chain sustainability.

Although innovation typically originates within firms, particularly at manufacturing sites, GPI in practice is frequently co-developed and operationalized across supply chain networks. In our study, the focus is on supply chain functions within manufacturing firms, where innovation is not only an internal process but also influenced by interactions with suppliers and logistics partners [5,13]. Supply chains enable innovation through mechanisms such as joint design initiatives, sustainable procurement, reverse logistics, and coordination of environmental standards across the value chain [21,29]. While the manufacturing function may physically implement innovations, the success of GPI often depends on how well supply chain partners integrate and support those efforts through aligned material flows, information sharing, and administrative innovations, such as green performance metrics and closed-loop systems [4,19]. Therefore, GPI is conceptualized here

as both a firm-driven and supply chain-enabled process, aligning with the view that SSCM fosters innovation beyond the firm boundary.

From an innovation perspective, adaptability facilitates shorter development cycles, enhances project flexibility, and reduces lead times. Supply chain adaptability and agility are interrelated, with adaptability focusing on long-term restructuring and agility addressing immediate needs [13]. The interplay between adaptation and agility enhances supply chain flexibility and overall efficiency. Given that adaptability promotes sustained strategic transformation, it is expected to produce enduring positive effects on supply chain ambidexterity [13].

Furthermore, adaptability in logistics management is acknowledged as a crucial factor in improving both environmental and financial performance in business [25]. The integration of Industry 4.0 (I4.0) capabilities enhances adaptability by enabling enterprises to develop innovative business models that align ecological responsibility with profit generation. Transformative strategies such as digital business transformation (DBT) and organizational ambidexterity (OA) promote adaptive processes, allowing organizations to proactively tackle sustainability issues [28].

Research findings indicate that companies that successfully replicate the best practices in supply chain adaptation attain improved business efficiency and enduring sustainability. Rojo et al. [24] found that firms with elevated adaptation levels demonstrate enhanced supply chain capabilities, leading to greater operational efficiency and sustainability performance.

Supply chain adaptability reflects a firm's capacity to implement long-term structural changes—such as reconfiguring logistics networks, modifying sourcing strategies, or integrating new technologies—to respond to persistent environmental or market shifts [13,22]. This capability is often rooted in a firm's absorptive capacity, which enables it to identify, assimilate, and apply external knowledge to reshape its operations [30]. However, absorptive capacity alone is not sufficient. To translate knowledge into action, firms rely on network competencies, which facilitate collaboration and learning across supply chain partners [17,31]. Together, these capabilities form the basis for adaptability, allowing firms to proactively align their operations with sustainability goals and regulatory demands. Adaptability therefore functions as a strategic dynamic capability that supports environmental responsiveness and long-term sustainable performance, particularly in the contexts of institutional or market turbulence [22,30].

From the perspective of DCT, adaptability enables firms to purposefully reconfigure resources and adjust organizational routines in response to environmental changes, which is essential for enabling innovation under sustainability constraints [22,30]. In the context of GPI, firms with high adaptability are more likely to recognize external environmental requirements, assimilate emerging green technologies, and realign their supply chain processes to facilitate eco-friendly product development [13,21]. Adaptability also supports long-term partnerships and learning networks, which are crucial for integrating sustainable materials, redesigning products for recyclability, and meeting regulatory standards [4,17]. As such, adaptability functions not just as a reactive capability but as a strategic enabler of green innovation, particularly in manufacturing supply chains facing institutional and environmental pressures. This theoretical linkage posits that supply chain adaptability positively influences green product innovation. Given the acknowledged importance of adaptability in supply chain reconfiguration, innovation, and sustainability, it is reasonable to propose the following hypotheses:

H1. *Supply chain adaptability positively influences supply chain sustainability.*

H2. *Supply chain adaptability positively influences GPI.*

2.2.2. Impact of Supply Chain Agility

Supply chain agility refers to an organization's ability to swiftly identify and respond to transient fluctuations in supply network and market conditions, such as demand variations, material shortages, and supplier delivery delays [11]. This responsiveness is achieved through rapid adjustments in production processes, reduced lead times for material substitution, and improved transportation capacity [17]. The ability of a supply chain to modify its strategy and operations in reaction to market fluctuations is crucial for sustaining competitiveness and resilience [18].

Supply chain agility is an essential driver of supply chain ambidexterity and operational efficiency. Jermsittiparsert and Pithuk [13] asserted that agility allows organizations to employ both exploratory (innovation-focused) and exploitative (efficiency-focused) supply chain strategies, yielding performance advantages. An agile supply chain enhances demand–supply synchronization, minimizes storage and shipping costs, and allows companies to tailor manufacturing to market demands. By reducing replenishment times for raw materials and services, improving production efficiency, and facilitating swift process modifications, companies can effectively manage inventory levels and avert markdowns caused by excess stock [10].

Within the framework of DCT, supply chain agility is defined as the firm's ability to sense changes in the environment and swiftly respond through flexible operational adjustments [10,22]. Agility allows firms to respond rapidly to regulatory shifts, customer demand for eco-friendly products, or sudden material shortages by modifying production processes, sourcing alternatives, or logistics operations [13,18]. This responsiveness is critical in enabling GPI, which often requires fast integration of sustainable materials, adjustments in packaging design, or coordination with suppliers for environmentally compliant inputs [5,21]. Unlike adaptability, which is strategic and long-term, agility operates at the tactical level, facilitating real-time changes that can accelerate the development and deployment of green products [4,30]. Therefore, agility supports the dynamic and iterative nature of GPI which posits that supply chain agility positively influences green product innovation.

Agility is essential in digital transformation. Alamsjah and Yunus [12] found that supply chain agility significantly enhances Supply Chain 4.0 (SC4.0) maturity and serves as a strong mediator in the relationship between supply chain ambidexterity and SC4.0 maturity. This suggests that firms with agile supply chains are more proficient at integrating new digital technologies and improving operations in a rapidly changing business environment. Eckstein et al. [17] demonstrated that agility, combined with flexibility, positively influences cost-effectiveness and operational performance, thereby highlighting agility's role in enhancing overall supply chain efficiency. The role of supply chain agility as a mediator has been thoroughly investigated in the literature. Alamsjah and Asrol [23] found that lean SC and agile SC fully mediate the relationship between SC ambidexterity and SC performance. Their research demonstrates that agile and lean supply chain methodologies aid organizations in navigating uncertainty by harmonizing stability with exploration and exploitation strategies. This is particularly vital in volatile supply chain contexts where agility allows firms to mitigate risks associated with delayed shipments, supply chain disruptions, and fluctuations in demand.

Beyond operational efficiency, supply chain agility improves environmental performance and sustainability. Mirghafoori et al. [32] demonstrated that agility mediates the relationship between administrative strategy, customer satisfaction, financial performance, and green supply chain performance. The research demonstrated that improvements in technology adoption, strategic goal setting, customer responsiveness, productivity, and environmental compliance collectively enhance organizations' ability to implement sus-

tainable supply chain practices. Zhao et al. [26] emphasized that leadership ambidexterity influences the connection between supply chain sustainability capabilities (SSC) and green innovation, indicating that an agile leadership approach enhances organizations' ability to implement environmentally sustainable initiatives.

Agility, as a short-term dynamic capability, allows firms to respond quickly to environmental demands and customer expectations by modifying operational routines and product configurations [11,17]. This responsiveness is critical for implementing green initiatives under time constraints, such as eco-labeling, rapid packaging redesign, or material substitutions, which align with market-facing sustainability pressures [18,32].

These observations suggest that supply chain agility is crucial for enhancing GPI and sustainable supply chains. Agile supply chains enable the swift integration of sustainable materials, the adoption of eco-friendly production methods, and the responsiveness to market demands for environmentally conscious products. Furthermore, agility enhances supply chain sustainability by reducing waste, optimizing resource utilization, and improving environmental compliance.

According to DCT, agility enables firms to sense and seize short-term opportunities by reconfiguring operational processes in response to rapidly changing environmental and market conditions [10,22]. In the sustainability context, this means firms can adjust sourcing strategies, redesign product lines, or shift to greener logistics practices in response to customer preferences, stakeholder pressure, or regulatory changes [13,18]. Supply chain agility thus serves as a critical enabler for supply chain sustainability, allowing firms to minimize environmental impact, improve resource efficiency, and ensure compliance without sacrificing responsiveness or service levels [4,5]. Unlike static capabilities that support routine operations, agility allows for real-time alignment of operations with sustainability objectives, which is particularly vital in volatile or uncertain environments [21,30]. This posits that supply chain agility positively influences supply chain sustainability. Therefore, based on the preceding discussion, the following assumptions are proposed:

H3. *Supply chain agility positively influences GPI.*

H4. *Supply chain agility positively influences supply chain sustainability.*

2.2.3. Impact of GPI on Supply Chain Sustainability

GPI signifies the development of environmentally sustainable products by integrating sustainability considerations, such as material efficiency and energy consumption, into the design process. It serves as a strategic tool enabling companies to attain a competitive advantage by enhancing their environmental and economic performance [21]. GPI seeks to mitigate negative environmental impacts throughout a product's lifecycle, from creation to disposal, by employing sustainable materials, efficient production processes, and eco-friendly product modifications [19].

Prior research highlights the critical role of GPI in improving economic and environmental outcomes [20]. Saudi et al. [33] demonstrated that environmentally sustainable product innovation and operational practices significantly enhance financial performance and ecological outcomes. Implementing GSCM allows organizations to achieve competitive advantages while fostering collaboration and synergy among internal and external stakeholders [2]. Cancela et al. [5] found that ambidextrous organizations, which adeptly balance exploration and exploitation, are more likely to achieve sustainable supply chain success through innovative and environmentally friendly product development. The increasing market demand for sustainable products boosts the profitability of green product development, highlighting its strategic importance in modern supply chains.

While there is empirical support for the role of GPI in enhancing sustainability performance, it is important to critically assess the causal mechanisms and boundary conditions of this relationship. Theoretically grounded in DCT, GPI acts as a capability deployment mechanism that allows firms to integrate environmental concerns into product development and translate innovation into sustainability outcomes [4,22]. However, the effectiveness of GPI in driving sustainability depends on several conditional factors, including regulatory intensity, stakeholder pressure, supply chain collaboration, and a firm's internal innovation climate [13,19,30]. For instance, in highly regulated industries or environmentally sensitive markets, GPI may have a stronger influence on sustainability outcomes due to external accountability pressures [5,21]. Moreover, firms with greater technological readiness or a strong culture of continuous improvement are more likely to achieve higher sustainability gains from GPI. Recognizing these contextual factors enhances the theoretical robustness of the positive relationship between GPI and supply chain sustainability.

Moreover, regulatory elements additionally facilitate the promotion of GPI. Chan et al. [19] found that environmental regulations substantially influence the development of sustainable products, leading to improved cost efficiency and productivity enhancements. The integration of environmental data and collaboration with supply chain partners substantially enhances companies' ability to implement green innovations. Zhang et al. [29] emphasized that green supplier integration (GSI) improves environmental coordination capabilities and promotes proactive engagement in new sustainability initiatives. Zhao et al. [26] highlighted that social capital derived from suppliers and consumers substantially influences sustainable exploitative innovation and green exploratory development.

Under the lens of DCT, GPI represents a firm's ability to integrate environmental objectives into the design and development of new products, enabling it to reconfigure processes in ways that align with evolving sustainability demands [4,22]. GPI contributes to supply chain sustainability by reducing resource consumption, enhancing recyclability, minimizing emissions, and complying with environmental regulations, all of which collectively improve the ecological performance of supply chain operations [5,19,21]. Moreover, GPI fosters a proactive sustainability mindset across the supply chain, encouraging firms to adopt green materials, energy-efficient technologies, and closed-loop logistics systems [13,30]. These innovation-led transformations are essential in achieving long-term sustainability goals and building competitive advantage in environmentally sensitive markets. This theoretical foundation supports the concept that green product innovation positively influences supply chain sustainability.

Therefore, GPI enhances sustainability by embedding environmental considerations into product development and manufacturing processes, leading to reduced emissions, improved resource efficiency, and compliance with regulatory standards [19,21,33]. By integrating lifecycle thinking and eco-design principles, GPI directly contributes to both environmental and economic dimensions of supply chain sustainability [20,29].

Given the substantial evidence supporting the importance of GPI in sustainability and supply chain effectiveness, the following hypothesis is proposed:

H5. *GPI positively influences supply chain sustainability.*

2.2.4. Mediating Role of GPI

GPI plays a crucial intermediary role in linking supply chain capabilities to sustainability outcomes. The development of eco-friendly products improves GSCM by reducing environmental impact throughout a product's lifecycle, starting from the design phase [34]. Sun and Sun [4] found that green supply chain innovation (GSCI) partially mediates the relationship between green innovation strategy and both exploratory and exploitative

green innovation, suggesting that companies may indirectly enhance the adoption of green innovation via GSCI.

The mediating role of GPI between supply chain ambidexterity and sustainability is theoretically justified through the lens of dynamic capabilities, which suggest that firms must reconfigure and integrate resources across internal and external networks to achieve competitive and sustainable advantages [22]. Adaptability enables long-term reconfiguration of supply chain structures and partnerships to support the development of environmentally sustainable products, while agility facilitates rapid alignment of production and logistics operations to shifting market and environmental demands [10,13]. However, neither adaptability nor agility guarantees sustainability outcomes unless they are strategically directed toward innovation.

GPI therefore acts as a translational mechanism linking dynamic supply chain capabilities to sustainability performance by embedding eco-efficiency, compliance, and market-driven environmental strategies into the product lifecycle [4,5,19]. This justifies the proposed mediation model in which GPI serves as the operational bridge between supply chain ambidexterity and supply chain sustainability.

Kara and Edinsel [21] identified GPI as a mediator in the connection between sustainable performance and GSCM. GPI specifically enables the linkage between GHRM and GSCM, highlighting its essential role in promoting long-term sustainability efforts. This underscores the importance of GPI as a connection between sustainability-oriented managerial practices and operational supply chain efficacy.

Emerging technologies also influence the intermediary role of GPI. Mohamed et al. [35] established that blockchain technology (BCT) significantly enhances sustainable supply chain performance (SCP). The effect is intensified when facilitated by supply chain resilience (SCR), customer integration, and sustainable consumer data exchange, indicating that green innovation processes are improved by digital transformation and supply chain collaboration.

Awwad et al. [36] found that green consumer collaboration, supplier integration, and innovative product adaptability significantly enhance long-term GPI. Furthermore, the creation of eco-friendly products mediates the relationship among these three attributes and firms' competitive advantage, highlighting that green innovation acts as both a catalyst for sustainability and an essential component of corporate success.

Aftab et al. [27] demonstrated that organizational ambidexterity (OA) indirectly influences sustainable development (SDE) through entrepreneurial orientation (EO). Their findings indicate that explorative innovation allows organizations to develop new sustainability-oriented competencies, while exploitative innovation improves existing knowledge and operational efficiency to ensure long-term sustainability.

Within the framework of DCT, firms achieve sustainable competitive advantage by transforming and reconfiguring operational capabilities to meet environmental and market demands [22]. While adaptability and agility serve as foundational dynamic capabilities, their direct impact on sustainability may be limited unless they are channeled through innovation-focused mechanisms [13,17]. GPI functions as one such mechanism that enables firms to convert the flexibility and responsiveness gained through adaptability and agility into eco-efficient, sustainable outputs [4,19]. For example, adaptability may provide the structural flexibility necessary to adopt new green technologies, but GPI translates that potential into actual product innovations that reduce environmental harm. Similarly, agility may enable firms to respond quickly to regulatory or consumer-driven sustainability demands, but GPI allows them to do so through innovative, environmentally conscious product solutions [21,30]. This mediating role reflects GPI's position as a capability deployment tool, linking supply chain dynamics to sustainable performance. Accordingly, it

proposes that GPI mediates the relationship between supply chain adaptability and supply chain sustainability, while positing that GPI mediates the relationship between supply chain agility and supply chain sustainability.

Therefore, GPI functions as a strategic mechanism that translates dynamic capabilities (agility and adaptability) into tangible sustainability outcomes by facilitating the development and deployment of environmentally conscious products and practices [4,5,19]. It bridges operational flexibility with strategic environmental performance, positioning innovation as a central lever in achieving sustainable supply chain goals [21,27]. This supports the notion that GPI serves as a crucial link between supply chain ambidexterity (adaptability and agility) and supply chain sustainability. In light of this discussion, the subsequent hypotheses are put forth:

H6a. *GPI mediates the relationship between supply chain adaptability and supply chain sustainability.*

H6b. *GPI mediates the relationship between supply chain agility and supply chain sustainability.*

Therefore, the following hypothesized model was developed as shown in Figure 1.

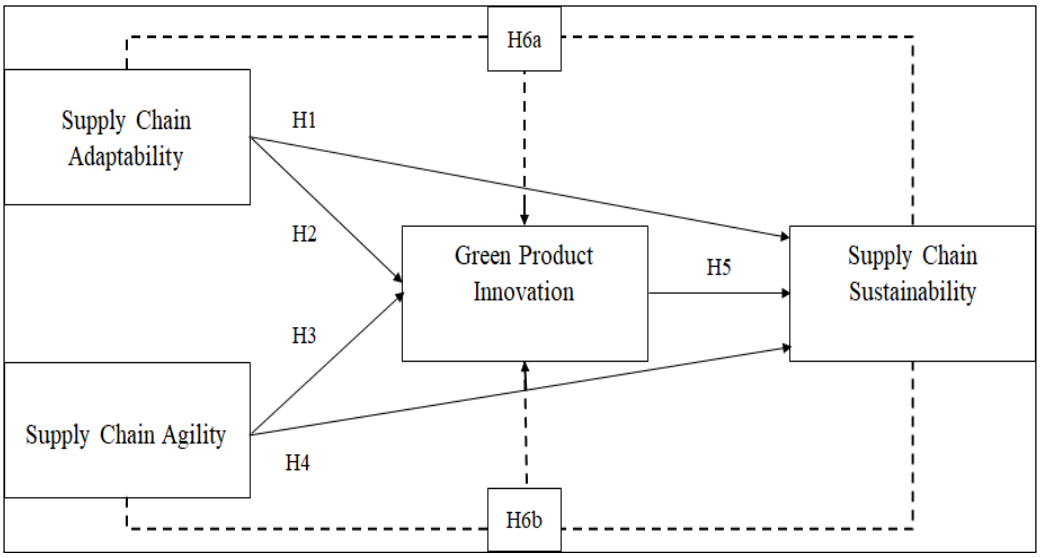

Figure 1. Conceptual framework (source: authors).

3. Methodology

3.1. Sampling Procedure

The sampling procedure in this study involved defining the sampling frame, selecting an appropriate sampling method, determining the sample size, and executing the data collection process. The target respondents were managers from various manufacturing firms operating in Amman, Jordan, the country's capital and largest industrial hub. These managers were chosen as they are directly involved in supply chain decision-making and have the necessary expertise to provide insights into supply chain adaptability, agility, GPI, and sustainability practices.

A non-probability (judgmental) sampling method was utilized to select participants. This strategy, as articulated by Malhotra [37], enables researchers to intentionally select participants based on their expertise, experience, and pertinence to the study objectives. A probability sampling approach was deemed unfeasible for this study due to the absence of a comprehensive and publicly accessible database of supply chain professionals across Jordanian manufacturing firms, as well as practical constraints related to time, cost, and access limitations in the field. Instead, we employed judgmental (expert) sampling, a

common approach in organizational and supply chain research when targeting informants with specific domain knowledge [33,34]. Respondents were selected based on their managerial roles in logistics, procurement, operations, or sustainability functions, ensuring that participants possessed the knowledge required to provide informed responses related to supply chain adaptability, agility, and green innovation. The firms represented spanned key sectors including food, chemicals, plastics, and printing accounting for the majority of Jordan's industrial activity. This sampling strategy enhances the reliability of the findings while reflecting the study's practical research context [31,35].

Despite its inherent limits on generalizability, non-probability sampling is a legitimate method for exploratory and theory-testing research, especially in business and management studies where obtaining a fully randomized sample can be difficult. Hair et al. [38] recommended a minimum sample size of 200 participants for Partial Least Squares Structural Equation Modeling (PLS-SEM). The study aimed to overcome this obstacle to enhance statistical power and the robustness of results.

A total of 346 valid responses were collected and assessed, yielding sufficient data for hypothesis testing and model validation. A structured questionnaire was created to collect data, employing established scales from prior research. Due to the absence of an institutional ethical review board (IRB) or formal research ethics committee for social science studies in the local academic context, this study did not undergo formal ethical approval. However, the study adhered to widely accepted ethical research standards. Informed consent was obtained from all participants prior to their involvement, and participation was strictly voluntary. Respondents were assured that their data would remain anonymous and confidential, and that the information collected would be used solely for academic purposes. No minors were involved in the study, and no sensitive personal data were collected. The lack of formal IRB oversight is noted as a contextual limitation, but ethical compliance was maintained in accordance with the principles outlined in the Declaration of Helsinki and related social science research guidelines [36,37].

The data collection process was conducted between June and October 2024 using a structured questionnaire distributed through Google Forms, a widely used and secure online survey platform. The survey link was disseminated via email invitations, and professional LinkedIn networks such as Jordan logistics network group, targeting supply chain professionals in Jordanian manufacturing firms. The participant pool was focused on their roles in supply chain, logistics, procurement, or operations to ensure relevance and expertise. To improve the response rate, one follow-up reminder was sent after four weeks following the initial distribution. Online administration was chosen for its efficiency, accessibility, and suitability for reaching geographically dispersed respondents, especially in light of limited in-person access and logistical constraints during the data collection period [38,39]. To improve response rates, anonymity and assurance that data will be used for scientific purposes only was assured to encourage faster and reliable responses.

3.2. Measurement Items

Several measurement items were adapted from established scales in previous studies to ensure the validity and reliability of the constructs examined in this research, as detailed in Table 2. The questionnaire was structured into two main sections. The first section collected demographic information about the respondents, including their job title, years of experience, company size, and industry sector. The second section contained the measurement items for the study variables, which were assessed using a 5-point Likert scale of agreement.

Table 2. Constructs and measurement items.

Constructs	Measurement Items	Sources
Supply Chain Adaptability	1. Analyzes global economies to identify emerging supply sources and markets. 2. Utilization of intermediaries to cultivate new suppliers and logistics infrastructure. 3. Assesses the requirements of end consumers, rather than solely those of direct clients. 4. Develops adaptable product designs. 5. Assesses the positioning of organizations' products within technological cycles and product lifecycles.	[10,17]
Supply Chain Agility	1. Our supply chain rapidly adapts to our evolving design requirements. 2. Our supply network promptly adapts to our fluctuating cost requirements. 3. Our supply chain promptly implements numerous product enhancements. 4. Our supply network promptly introduces new products to the market. 5. Our supply network adeptly adjusts manufacturing capacity.	[10,11,39]
Green product innovation (GPI)	1. Employing reduced or non-polluting/toxic substances (Utilizing eco-friendly products). 2. Enhancing and devising eco-friendly packaging (e.g., reduced paper and plastic material usage) for both existing and new items. 3. Retrieval and recycling of the company's obsolete products. 4. Adopting eco-labeling.	[19,21]
Supply Chain Sustainability	1. Revenue and market share have been significantly improved. 2. Operational expenditure of our firm has significantly decreased. 3. Paper usage and energy consumption in our enterprise have been significantly reduced. 4. Firms' compliance with environmental standards has been improved. 5. Reputation and image of the organization have been improved. 6. Relationship between the community and stakeholders has been improved.	[20,22,40]

4. Findings

4.1. Descriptive Analysis

The descriptive statistics presented in Table 3 include means, standard deviations, skewness, and kurtosis for each construct. The mean values suggest moderately high agreement among respondents on key constructs, such as supply chain agility and green product innovation, indicating their perceived relevance in the organizational context. The standard deviations reflect acceptable variation, suggesting a good level of response dispersion suitable for structural modeling. Skewness and kurtosis values for all items fall within the acceptable range of ± 2, as recommended for large-sample SEM applications [40,41]. These results indicate that the data do not exhibit severe non-normality. While PLS-SEM does not require multivariate normality, the observed levels of skewness and kurtosis still affirm the reliability and suitability of the dataset for variance-based SEM techniques [42]. Therefore, the descriptive statistics not only provide insight into the data distribution but also support the appropriateness of proceeding with the structural model analysis.

Table 3. Descriptive statistics (N = 346).

Constructs	Mean	Std. Deviation	Skewness	Std. Error	Kurtosis	Std. Error
Supply Chain Adaptability	3.7873	0.95563	−1.238	0.131	1.371	0.261
Supply Chain Agility	3.9647	0.95050	−1.643	0.131	2.490	0.261
GPI	4.0007	0.93415	−1.614	0.131	2.202	0.261
Supply Chain Sustainability	3.6479	1.00780	−1.230	0.131	0.750	0.261

Figure 2 presents the distribution of the sample across four key industry sectors, highlighting a concentration in the Food and Supply sector, which comprises 39.9% of the total sample. This is followed by the Chemicals sector at 24.9%, Plastic Products at 18.2%, and Printing and Paper at 17.1%. The data indicate that the sample is heavily weighted toward industries with high environmental and operational significance in Jordan's manufacturing landscape.

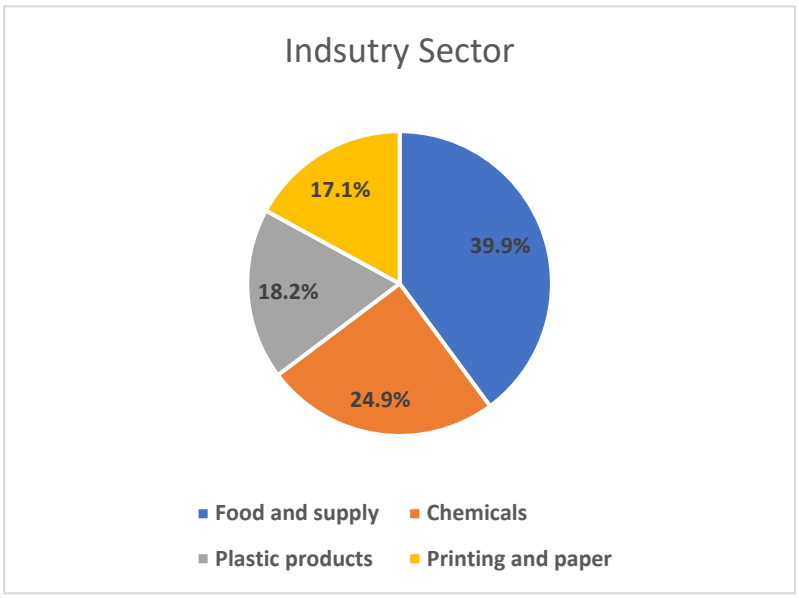

Figure 2. Industry sector (source: authors).

4.2. Structural Equation Modeling

In the two-stage procedure of structural equation modeling, both the structural model and the measurement model were applied. The analysis was carried out using SmartPLS version 4 of the statistical software [41].

4.2.1. Measurement Model Analysis

Convergent validity through average variance extracted (AVE), construct reliability by Cronbach's alpha, and composite reliability were assessed. All reliability values exceeded the required threshold (>0.70) [38]. The findings indicated that factor loading values surpassed 0.70 and AVE values exceeded 0.50 (see Table 4), confirming the convergent validity of the data [38].

Table 4. Construct reliability and validity.

Constructs	Items	Factor Loadings	Cronbach's Alpha	Composite Reliability	AVE
GPI	GPI.1	0.953	0.966	0.975	0.909
	GPI.2	0.961			
	GPI.3	0.954			
	GPI.4	0.944			
Supply Chain Adaptability	SC.AD1	0.950	0.967	0.974	0.882
	SC.AD2	0.944			
	SC.AD3	0.920			
	SC.AD4	0.933			
	SC.AD5	0.948			
Supply Chain Sustainability	SC.SUS1	0.960	0.975	0.980	0.891
	SC.SUS2	0.947			
	SC.SUS3	0.930			
	SC.SUS4	0.964			
	SC.SUS5	0.955			
	SC.SUS6	0.906			
Supply Chain Agility	SCA.1	0.972	0.976	0.982	0.914
	SCA.2	0.931			
	SCA.3	0.952			
	SCA.4	0.959			
	SCA.5	0.965			

Discriminant validity was investigated. According to Fornell and Larcker [42], the results shown in Table 5 below proved the discriminant validity of the constructs.

Table 5. Discriminant validity—Fornell–Larcker.

Constructs	1.	2.	3.	4.
1. Green Product Innovation	0.953			
2. Supply Chain Adaptability	0.517	0.939		
3. Supply Chain Agility	0.616	0.726	0.956	
4. Supply Chain Sustainability	0.616	0.467	0.572	0.944

In addition to the Fornell–Larcker criterion, we applied the Heterotrait–Monotrait (HTMT) ratio to assess discriminant validity, as it is widely recognized as a more reliable method in recent PLS-SEM applications. All HTMT values were below the recommended threshold of 0.85, indicating strong discriminant validity among the constructs. We also examined indicator cross-loadings, which confirmed that each item loaded highest on its intended construct relative to others as shown in Table 6.

Table 6. Discriminant validity—HTMT.

Constructs	1.	2.	3.	4.
1. Green Product Innovation				
2. Supply Chain Adaptability	0.534			
3. Supply Chain Sustainability	0.633	0.481		
4. Supply Chain Agility	0.633	0.748	0.586	

4.2.2. Measurement Model Analysis

The bootstrapping approach was used to run the structural model in SmartPLS with 5000 sub-samples as shown in Figure 3. Byrne [43] stated that NFI should be greater than 0.90 and SRMR should be less than 0.09. The model fit metrics showed that the PLS analysis could yield SRMR (0.024) and NFI (0.942) [38].

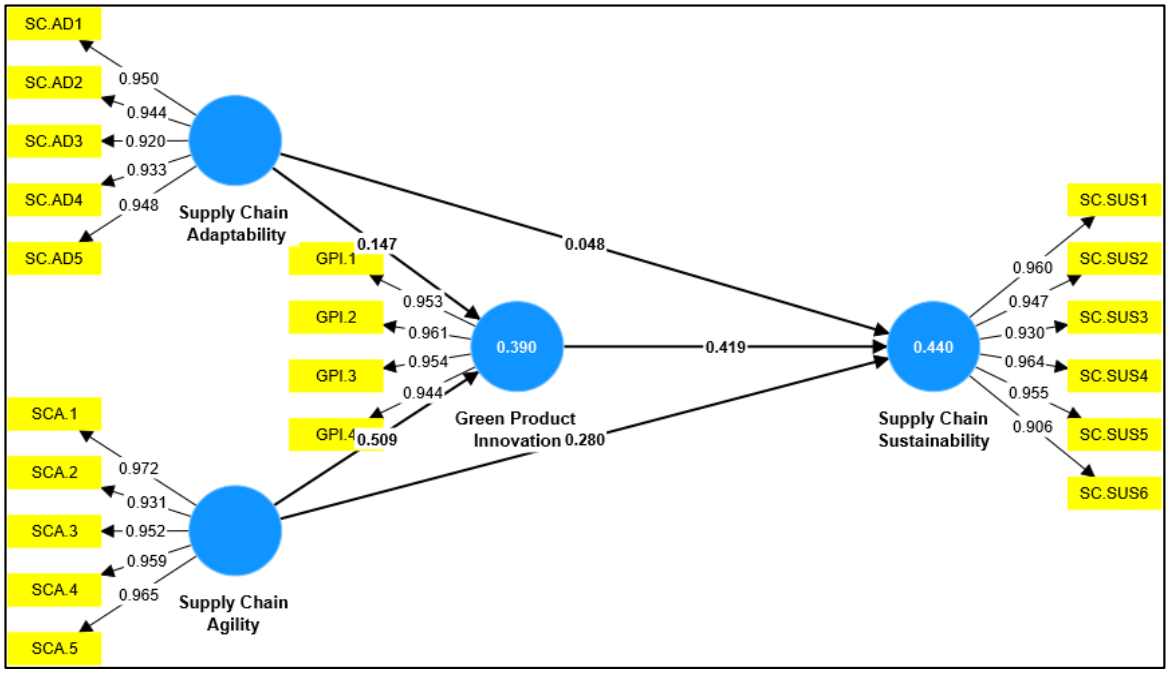

Figure 3. Final model diagram (source: authors).

The hypothesis testing results revealed varying levels of support for the proposed relationships based on t-values and *p*-values as shown in Table 7. H1 (t = 0.806, $p = 0.420$) was rejected, indicating that supply chain adaptability does not significantly influence supply chain sustainability. However, H2 (t = 2.773, $p = 0.006$) was supported, suggesting a significant positive relationship between supply chain adaptability and GPI. Both H3 (t = 7.777, $p = 0.000$) and H4 (t = 4.177, $p = 0.000$) were supported, demonstrating that supply chain agility plays a strong role in enhancing both GPI and supply chain sustainability. Additionally, H5 (t = 6.495, $p = 0.000$) confirmed that GPI significantly contributes to supply chain sustainability. Regarding mediation effects, H6a (t = 2.404, $p = 0.016$) and H6b (t = 5.617, $p = 0.000$) were both supported, indicating that GPI significantly mediates the relationships between supply chain adaptability, supply chain agility, and supply chain sustainability. These findings underscore the critical role of supply chain agility and GPI in driving sustainable supply chain performance.

To assess the mediating role of green product innovation (GPI) in the relationships between supply chain adaptability, agility, and sustainability, we used the bootstrapping method with 5000 resamples and reported bias-corrected 95% confidence intervals for the indirect effects. This approach is widely recommended for mediation testing in PLS-SEM, as it does not rely on the assumption of normality. The results indicated that the indirect effects were significant for both H6a and H6b, confirming GPI as a mediating variable. Additionally, we have provided a structural model path diagram displaying the standardized path coefficients (β-values), which visually summarizes the strength and direction of relationships among all latent variables.

Table 7. Results of the structural model.

Paths	Beta	t-Statistics	*p*-Values	Results
H1. SC Adaptability -> SC Sustainability	0.048	0.806	0.420 n.s.	Not Supported
H2. SC Adaptability -> GPI	0.147	2.773	0.006 **	Supported
H3. SC Agility -> GPI	0.509	7.777	0.000 ***	Supported
H4. SC Agility -> SC Sustainability	0.280	4.177	0.000 ***	Supported
H5. GPI -> SC Sustainability	0.419	6.495	0.000 ***	Supported
H6a. SC Adaptability -> GPI -> SC Sustainability	0.062	2.404	0.016 *	Supported
H6b. SC Agility -> GPI -> SC Sustainability	0.213	5.617	0.000 ***	Supported

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s. = not significant; (two-tailed test).

Moreover, to enhance the interpretation of the results, we assessed effect sizes (f^2) for all hypothesized relationships alongside t-values and *p*-values. For H1, the relationship between supply chain adaptability and sustainability was not statistically significant ($p > 0.05$), and the effect size was negligible ($f^2 < 0.02$), suggesting that adaptability alone has minimal direct influence on sustainability outcomes in this context. For H2, the relationship between adaptability and GPI showed a small but meaningful effect ($f^2 \approx 0.05$), indicating that adaptability supports innovation, particularly through long-term collaboration and reconfiguration. H3 and H4, concerning the impact of agility on GPI and sustainability, demonstrated moderate effect sizes ($f^2 \approx 0.10$–0.15), confirming the practical significance of agility as a dynamic capability that enables immediate responsiveness to sustainability-related demands. H5 also revealed a moderate effect ($f^2 \approx 0.12$), supporting the role of GPI in achieving sustainability goals. For the mediation hypotheses, H6a and H6b, the indirect effects were significant and the effect sizes were meaningful, reinforcing the conclusion that GPI is a critical mechanism that translates both adaptability and agility into sustainable outcomes. Overall, the effect size analysis strengthens the robustness of the model and provides insights into the relative influence and practical utility of each supply chain capability.

5. Discussion

Ambidexterity requires adaptability, experimentation, and strategic flexibility. This will aid companies in navigating competitive landscapes characterized by technological advancements and evolving market demands. Organizations are increasingly recognizing the imperative of integrating supply chain sustainability into their operations to meet stakeholder expectations, attain social legitimacy, and maintain competitive advantages [2,6].

The results indicated that H1 was not supported, suggesting that supply chain adaptability did not have a significant direct impact on supply chain sustainability. This finding contradicts earlier studies [10,12,13,17,24], which have emphasized that adaptability enables organizations to navigate persistent structural changes and enhance supply chain sustainability outcomes. However, this divergence can be better understood through contextual and theoretical lenses. In developing economies such as Jordan, manufacturing firms often face institutional voids, weak regulatory enforcement, and limited technological infrastructure—conditions that may constrain the strategic potential of adaptability to drive supply chain sustainability directly. While firms may possess the capacity to reconfigure supply chains or diversify sourcing, the lack of environmental regulations or market pressure may disincentivize firms from aligning such structural changes with green objectives. Additionally, adaptability as a dynamic capability may yield results only when it is paired with innovation-focused mechanisms, such as GPI, or embedded within supportive organizational culture and institutional environments [30]. Therefore, in the absence of external

motivators or resource availability, adaptability alone may be insufficient to foster supply chain sustainability in practice.

The results confirmed that H2 was supported, underscoring the importance of adaptability in enabling GPI. This aligns with Sun and Sun [4], who argued that green innovation strategies require both internal reconfiguration capabilities and external collaborative ties. Adaptive supply chains are more capable of establishing long-term partnerships and cross-functional collaborations—key enablers of eco-friendly product development [15]. In the Jordanian context, this suggests that while adaptability may not immediately translate into supply chain sustainability, it plays a foundational role in cultivating innovation environments where sustainable practices can emerge, particularly through joint design with suppliers and exploration of alternative production technologies.

The research further validated H3, indicating that agility substantially enhances the progression of environmentally sustainable product development. This supports the findings of Cancela et al. [5], who emphasized agility's role in balancing exploration and exploitation strategies within supply networks. Agility, as a dynamic capability, allows firms to respond quickly to environmental shifts, including changing regulations, consumer preferences, and technological innovations. This responsiveness enables firms to rapidly incorporate supply chain sustainability features into products, production lines, and logistics systems. Zhang et al. [29] similarly emphasized that supply chain agility strengthens green supply chain integration (GSCI), facilitating supplier collaboration and customer engagement, both of which are essential for successful GPI.

H4 was also supported, reinforcing the strategic significance of agility in enhancing supply chain sustainability. As Wamba et al. [10] as well as Alamsjah and Yunus [12] observed, agile supply chains improve resource allocation, reduce waste, and support timely adaptation to environmental disruptions. In contrast to adaptability, which involves long-term strategic change, agility operates tactically and facilitates immediate alignment of operations with supply chain sustainability goals. This distinction is particularly relevant under DCT, where agility reflects a firm's capacity to seize opportunities and reconfigure short-term processes. Jermsittiparsert and Pithuk [13] further highlighted that agility improves supplier coordination and inventory management, mitigating both financial and environmental risks and reinforcing its utility in sustainable supply chain management (SSCM).

To enhance conceptual clarity, this study provides a clearer demarcation between short-term responsiveness (agility) and long-term strategic adjustment (adaptability) within the supply chain context. Agility refers to an organization's ability to quickly respond to immediate disruptions, fluctuating customer demands, or regulatory changes through rapid operational adjustments and process flexibility. In contrast, adaptability involves a more gradual, strategic reconfiguration of supply chain structures such as developing new supplier networks, relocating facilities, or investing in new technologies to address sustained environmental or market shifts. For example, in the Jordanian food processing industry, firms often demonstrate agility by adjusting production lines to meet seasonal demand or regulatory changes regarding packaging and labeling. Meanwhile, adaptability is reflected in long-term investments in solar-powered facilities or in shifting toward biodegradable materials, enabling firms to align with supply chain sustainability goals and future-proof their operations. By distinguishing these two dimensions, the study underscores how agility drives immediate innovation and supply chain sustainability outcomes, while adaptability facilitates strategic capability development over time.

The study also confirmed H5, demonstrating that GPI significantly enhances supply chain sustainability. This aligns with Al-Khawaldah et al. [2], who found that green supply chain management improves competitive advantage and enhances collaboration across

the value chain. Similarly, Cancela et al. [5] and others underscore the role of product-level innovation in embedding supply chain sustainability into business models. By incorporating supply chain sustainability principles into product design, firms can reduce environmental impacts, enhance compliance, and strengthen stakeholder relationships. Moreover, the role of supply chain integration in supporting innovation is critical, as it enables the diffusion of green technologies and knowledge among partners, thereby amplifying the impact of innovation on supply chain sustainability outcomes [44].

The research also confirmed the mediating role of GPI in the relationships between both supply chain adaptability (H6a) and agility (H6b) and supply chain sustainability performance. These findings are consistent with prior studies that identify GPI as a central conduit through which operational capabilities influence environmental and performance outcomes [4,19,21,33,36]. Chan et al. [19] emphasized that GPI not only improves cost efficiency but also contributes to long-term competitiveness through sustainable innovation. Sun and Sun [4] similarly observed that green supply chain innovation (GSCI) plays a mediating role between strategy and product development, highlighting the importance of innovation as a transformational mechanism. Additionally, Kara and Edinsel [21] showed that GPI is critical in linking green human resource management (GHRM) to broader supply chain sustainability goals, reinforcing the view that GPI represents a dynamic capability that channels internal competencies into environmental outcomes. From a DCT perspective, this underscores the central premise that dynamic capabilities must be deployed through innovation to generate sustainable competitive advantage. Our findings extend this theory by showing that GPI amplifies the impact of both agility and adaptability, translating these abstract capabilities into measurable supply chain sustainability outcomes.

Thus, the results suggest that agility may outperform adaptability in driving supply chain sustainability directly particularly in contexts where immediate responsiveness and market reactivity are critical. This distinction reinforces the value of DCT in not only explaining the development of capabilities, but also in identifying the mechanisms (like GPI) through which these capabilities yield strategic outcomes. By uncovering this differentiation, the study adds theoretical nuance to DCT and contributes practical insights for firms in emerging markets aiming to balance flexibility, innovation, and environmental performance.

Therefore, to further enrich the theoretical implications, this study highlights the distinct roles of agility and adaptability as dynamic capabilities in driving GPI and supply chain sustainability, consistent with the foundations of DCT. The findings reveal that agility has a direct and strong influence on both GPI and supply chain sustainability, emphasizing its role in enabling rapid responses to market shifts, regulatory demands, and customer preferences. In contrast, adaptability influences supply chain sustainability only indirectly through GPI, suggesting that long-term structural flexibility alone is insufficient in achieving supply chain sustainability goals unless it fosters innovation. This differentiation advances DCT by illustrating how short-term responsiveness (agility) and long-term capacity reconfiguration (adaptability) contribute through distinct pathways, reinforcing the importance of viewing dynamic capabilities not as interchangeable, but as complementary drivers of sustainable innovation.

Table 8 is organized by hypothesis and shows how this study's findings are consistent or inconsistent with previous research.

Table 8. Summary of hypotheses and comparison with previous studies.

Hypothesis	The Study's Finding	Related Studies	Consistency/Difference
H1: Supply chain adaptability → Supply chain sustainability	Not supported	[10,12,13,17,24]	Differs—prior studies found a significant direct effect; this study suggests adaptability alone is insufficient without green innovation.
H2: Supply chain adaptability → GPI	Supported	[4,15,21]	Consistent—aligns with findings that adaptability enables collaboration and technology adoption essential for green innovation.
H3: Supply chain agility → GPI	Supported	[5,13,29]	Consistent—confirms agility enhances responsiveness to supply chain sustainability demands and facilitates innovation.
H4: Supply chain agility → Supply chain sustainability	Supported	[10,12,13]	Consistent—reinforces the role of agility in improving supply chain responsiveness, efficiency, and environmental outcomes.
H5: GPI → Supply chain sustainability	Supported	[2,5,19,21,33]	Consistent—echoes prior work showing that eco-friendly product development improves supply chain sustainability performance.
H6a: GPI mediates SC adaptability → SC sustainability	Supported	[4,21]	Partial alignment—prior work suggested indirect effects; this study confirms the mediation empirically in a Jordanian context.
H6b: GPI mediates SC agility → SC sustainability	Supported	[4,19,33,36]	Consistent—supports the bridging role of GPI between agile capabilities and supply chain sustainability outcomes.

Managerial Implications

This study provides a set of empirically grounded managerial implications for manufacturing firms in Jordan, with particular emphasis on the roles of supply chain adaptability, agility, and GPI in shaping sustainable performance. Rather than offering general prescriptions, the implications outlined here are specifically informed by the contextual nuances and sectoral dynamics observed in the Jordanian industrial landscape.

First, the findings underscore that adaptability alone does not automatically yield sustainability benefits. While adaptable supply chains allow firms to restructure their operations, switch suppliers, or relocate production facilities, these activities do not inherently lead to improved environmental performance unless they are deliberately aligned with sustainability goals. For instance, shifting to alternative suppliers or production methods may enhance operational flexibility, but if these decisions are not informed by environmental considerations—such as supplier carbon footprint, energy efficiency, or compliance with environmental regulations—their impact on sustainability will remain limited. Managers should therefore ensure that supply chain reconfiguration efforts are guided by eco-strategic objectives, including green procurement standards, lifecycle assessments, and sustainability certifications. This is especially critical in a country like Jordan, where formal environmental governance mechanisms are still developing, and firm-led initiatives can fill institutional voids.

Second, adaptability serves as an important enabler of green product innovation, particularly when leveraged to support experimentation, collaboration, and long-term capability development. Managers in Jordanian manufacturing firms can capitalize on this by developing flexible sourcing partnerships with green suppliers, investing in new material technologies, and supporting internal R&D initiatives focused on sustainability. For example, firms in the chemicals and plastics sectors can use adaptability to integrate biodegradable materials or reformulate products to comply with tightening environmental regulations. Similarly, food manufacturers can respond to rising demand for sustainable

packaging and traceability by collaborating with local and regional partners on innovative product redesigns. In these contexts, adaptability functions not only as an operational asset, but also as a strategic platform for advancing environmental innovation over time.

Third, the study clearly demonstrates that agility plays a more immediate and impactful role in achieving sustainable outcomes. This means that firms capable of quickly sensing and responding to shifts in market demands, regulatory changes, and resource constraints are better positioned to implement sustainability measures effectively. Agility enables rapid adjustment of production processes, swift supplier coordination, and efficient inventory management—each of which supports leaner, greener operations. Jordanian firms can strengthen supply chain agility by adopting digital tools for real-time monitoring, integrating supplier collaboration platforms, and embedding predictive analytics into demand forecasting and production planning. These practices not only improve responsiveness but also help reduce overproduction, energy waste, and excess inventory, making sustainability gains both achievable and cost-effective.

Fourth, the strong and direct influence of green product innovation on sustainability performance highlights the need for firms to embed environmental considerations into the core of their product development strategies. Managers should actively pursue product design initiatives that prioritize biodegradable inputs, recyclability, and energy-efficient manufacturing. Incorporating lifecycle thinking into product development can also help firms anticipate and mitigate downstream environmental impacts. Moreover, firms can draw from circular economy principles by developing models for reuse, remanufacturing, and closed-loop recycling. These strategies are particularly applicable in printing and packaging, where innovations in eco-friendly inks, sustainable paper sourcing, and water conservation technologies can significantly reduce environmental burdens while meeting evolving market expectations.

Additionally, the study emphasizes that GPI is not only an outcome of supply chain capabilities but also a strategic mechanism through which sustainability is achieved. For GPI to translate supply chain responsiveness into measurable sustainability outcomes, firms must invest in digital transformation and advanced manufacturing technologies. Tools such as IoT for resource tracking, blockchain for traceability, and AI for process optimization can enhance transparency and support continuous improvement in environmental performance. Policymakers and business associations in Jordan can play a catalytic role by facilitating access to these technologies through public–private partnerships, innovation grants, and sustainability-oriented industrial zones.

The study also reveals that the role of GPI varies significantly across Jordan's dominant manufacturing sectors. In the food and supply sector, GPI enables firms to reduce packaging waste, improve shelf-life, and respond to growing consumer preference for organic and ethically sourced products. In the chemical industry, it supports the development of eco-friendly formulations and minimizes hazardous emissions through cleaner production processes. In plastic products manufacturing, GPI is essential for developing alternatives to single-use plastics, such as compostable or bio-based materials. In the printing and paper sector, innovation drives the adoption of sustainable raw materials, eco-friendly printing technologies, and water-efficient production methods. Sector-specific strategies must be developed to match the unique challenges and sustainability drivers of each industry.

Finally, the findings point to the critical importance of building a sustainability-oriented organizational culture. Firms must integrate green human resource management (GHRM) practices to support long-term change. This includes providing sustainability training for employees at all levels, embedding environmental goals into performance appraisal systems, and offering incentives for cross-departmental innovation initiatives. Managers should also foster collaboration between operations, R&D, and supply chain

teams to ensure that sustainability objectives are embedded throughout the value chain. Participation in regional sustainability networks and international industry alliances can further enhance knowledge exchange, improve benchmarking, and strengthen the collective movement toward sustainable manufacturing in Jordan.

Thus, the findings of the study underscore that achieving sustainable supply chain performance in Jordanian manufacturing requires more than structural flexibility, which demands a coordinated, innovation-led approach, backed by digital technologies, organizational commitment, and targeted policy support. Managers must treat GPI not as a compliance task, but as a strategic pathway to long-term competitiveness and resilience in an increasingly sustainability-driven global market.

These findings offer valuable lessons for managers and policymakers in other developing countries facing similar institutional constraints and resource limitations. By aligning supply chain agility and GPI with national sustainability agendas, they can foster industrial transformation that supports both economic growth and environmental resilience in these countries.

6. Conclusions

This study aimed to examine the relationships among supply chain adaptability, supply chain agility, GPI, and supply chain sustainability in manufacturing firms in Jordan. The research specifically investigated the influence of supply chain ambidexterity (adaptability and agility) on GPI and sustainability, as well as the mediating role of GPI in these interactions. Given the increasing pressure on companies to adopt sustainable practices, both academia and industry must understand how supply chain capabilities improve environmental and operational sustainability. The research utilized a quantitative methodology, employing Partial Least Squares Structural Equation Modeling (PLS-SEM) to analyze survey data collected from 346 supply chain managers in Jordanian manufacturing firms. A structured questionnaire was created using established measurement scales, and the study employed a purposive sampling method to select participants with relevant supply chain experience.

The findings revealed that supply chain adaptability does not have a significant direct impact on supply chain sustainability, contradicting some prior studies that emphasized adaptability as a key enabler of sustainability. However, adaptability was found to positively influence GPI, suggesting that firms with adaptable supply chains are better positioned to develop eco-friendly products. In contrast, supply chain agility played a direct and significant role in both GPI and supply chain sustainability, highlighting the importance of responsiveness and flexibility in achieving sustainability goals. Additionally, GPI significantly contributed to supply chain sustainability and served as a mediator between supply chain ambidexterity (both adaptability and agility) and sustainability. These results emphasize that GPI is a crucial enabler that links operational flexibility to sustainability outcomes.

Despite its contributions, this study has several limitations that provide opportunities for future research. First, while the study employed a non-probability (judgmental) sampling method to target knowledgeable respondents within Jordanian manufacturing firms, this approach may limit the generalizability of the findings to the broader industrial population. As such, caution should be exercised when extrapolating the results beyond the sampled sectors or geographic region. Future research could enhance generalizability by employing probability-based sampling techniques and conducting comparative studies across different regions or industrial sectors to capture potential variations in green product innovation and sustainability practices to enhance representativeness and increase external validity. Second, this study focused solely on manufacturing firms in Jordan, limiting

cross-industry and cross-regional applicability. Future studies should expand the research scope to other industries, such as retail, healthcare, and logistics, and explore comparative analyses across different economic and regulatory environments to assess the generalizability of the proposed relationships. Third, while this study examined the mediating role of GPI, it did not explore potential moderating factors that might influence the strength of these relationships. Future studies should investigate the moderating effects of industry regulations, market competition, digital transformation, and environmental policies to provide a more nuanced understanding of how supply chain ambidexterity contributes to sustainability.

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