sustainability

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The Path from Green Innovation to Supply Chain Resilience: Do Structural and Dynamic Supply Chain Complexity Matter?

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Abstract: At the heart of supply chain innovation lies the challenge of complexity, a pivotal force shaping the pathways to resilience and sustainable success in today's business environment. Drawing from the resource-based view, dynamic capabilities, and contingency theories, this study examines the impact of green innovation strategies on supply chain resilience through the mediation role of green logistics management practices and the moderation effects of dynamic and structural supply chain complexity. Leveraging a quantitative approach, this study surveyed 404 managers from manufacturing firms in Turkey using a combination of physical and electronic questionnaires. Our analysis robustly supports the interconnected roles of green innovation strategy and logistics management practices in bolstering supply chain resilience. A green innovation strategy significantly enhances green logistics management practices and supply chain resilience. Further, green logistics practices contribute positively to supply chain resilience, acting as a crucial mediator in translating green innovation strategies into heightened supply chain resilience. Additionally, the effectiveness of green innovation strategies in improving green logistics management practices is amplified in less structurally complex supply chains. In contrast, the impact of green logistics practices on supply chain resilience becomes more pronounced in environments with lower dynamic complexity, highlighting the nuanced influence of supply chain complexity on sustainability efforts. The study's findings contribute a novel perspective to the sustainability discourse, emphasizing complexity's nuanced role as a determinant of supply chain resilience.

Keywords: green innovation strategy; supply chain resilience; green logistics management practices; structural supply chain complexity; dynamic supply chain complexity; Turkish manufacturing

Citation: Issa, A.; Khadem, A.; Alzubi, A.; Berberoğlu, A. The Path from Green Innovation to Supply Chain Resilience: Do Structural and Dynamic Supply Chain Complexity Matter? *Sustainability* **2024**, *16*, 3762. https://doi.org/10.3390/su16093762

Academic Editors: Jianhua Zhu, Jiaoping Yang, Chaoan Lai and Yanming Sun

Received: 19 March 2024
Revised: 22 April 2024
Accepted: 25 April 2024
Published: 30 April 2024

1. Introduction

The integration of green innovation into supply chains represents a significant transition towards sustainability and resilience in the ever-changing global commerce landscape. Sustainability encompasses a multidimensional approach that considers environmental, social, and economic factors [1]. This study focuses on the sustainability of supply chain management practices within manufacturing firms in Turkey, particularly in the context of green innovation strategies and their impact on supply chain resilience. The integration of green innovation into supply chains combines environmentally friendly practices with technological advancements to reduce environmental effects and improve operational effectiveness [2,3]. The integration of sustainable practices across industries and the driving of transformation are contingent upon collaboration among stakeholders, encompassing suppliers and consumers [4]. These initiatives, observed across different industries, not only demonstrate corporate responsibility but also establish green innovation as a crucial strategic resource for reducing carbon footprints, optimizing resource utilization, and promoting circular economies. This affirms its role as more than just an ethical commitment but also as a key competitive strategy [3–5].

The endorsement of the Turkey Green Industry Project by the World Bank [6] enhances the significance of this research, as it focuses on the development of a sustainable and resilient industrial sector. Turkey's dedication to environmental sustainability is emphasized in its updated first Nationally Determined Contribution [7], which aligns with the country's commitment to sustainable practices and innovation.

The integration of sustainable development principles, specifically green logistics and innovation, within the realm of supply chain management is of paramount importance in order to enhance operational efficiency and foster collaboration. Supply chain management (SCM) plays a pivotal role in facilitating the implementation of green innovation strategies and enhancing supply chain resilience [8]. SCM involves the coordination and integration of various activities across the supply chain, from sourcing raw materials to delivering finished products to end customers. With the growing emphasis on sustainability, companies are increasingly adopting green practices within their supply chain operations [9]. Song et al. [10] emphasize the efficacy of platform-based strategies and technological advancements in facilitating the implementation of environmentally friendly and sustainable supply chain management practices, with a particular emphasis on data-driven methodologies. Sustainable supply chain management (SSCM) can be defined as the strategic integration of environmentally and socially responsible practices throughout the entire supply chain lifecycle, from sourcing raw materials to delivering the final product to customers. This approach aims to minimize the environmental impact, conserve resources, promote social responsibility, and enhance economic viability along the supply chain [11]. Sustainable supply chain management encompasses various aspects such as eco-friendly sourcing, green manufacturing processes, efficient transportation and distribution, ethical labor practices, waste reduction, and the adoption of renewable energy sources [12]. Hongquan and Abdullah [13] provide a comprehensive analysis of the beneficial effects of green supply chain management (GSCM) practices on the food industry's performance, emphasizing the significance of environmentally sustainable logistics. Mathu [2] argues in favor of adopting a triple-bottom line framework that incorporates economic, environmental, and social considerations, which are essential for the development of effective and robust supply chains. A study by Klimkiewicz and Nowak [14] on the role of corporate social responsibility (CSR) in supply chain management and Bouhlel et al. [15] on the strategic use of packaging design to improve logistics efficiency make the need for sustainable practices even stronger. The study conducted by Onyinkwa and Ochiri [16] serves as a prime example of the competitive and financial benefits associated with environmental collaboration and the adoption of green production methods. This research underscores the worldwide shift towards sustainability in response to the challenges posed by climate change and the depletion of resources.

Academic research in green supply chain management (GSCM) has revealed a notable need for comprehending the complex relationship between green innovation strategies and logistics management within diverse supply chain complexities. Ye and Lau [3] examine the effect of supply chain attributes on adopting environmentally friendly solutions in the electronics sector, highlighting the role of complex structural factors in green supply chain management (GSCM). Sellitto [17] presents a theoretical framework for evaluating the efficacy of environmentally sustainable practices, focusing on the interplay between green strategy, innovation, and operational aspects. Nureen et al. [18] completed more research in the manufacturing sectors of emerging economies to look into how collaboration and new eco-technological technologies affect the performance of green supply chain management (GSCM), focusing on how complex things change over time. According to Aroonsrimorakot and Laiphrakpam's [19] study, there is a significant correlation between the efficacy of green supply chain management (GSCM) practices and the structural simplicity of supply chains. This highlights the importance of further research to explore the collective impacts of green innovation and logistics in complex supply chain settings.

In accordance with existing research, the complexity of supply chains, encompassing factors such as structural and dynamic complexities, plays a pivotal role in shaping the adoption and efficacy of green innovation strategies within manufacturing firms [20]. This, in turn, significantly influences the resilience of the supply chain networks. For instance, Huang et. al. [21] demonstrated that structural supply chain complexity, including aspects such as network configuration and interdependencies, can impact the implementation and success of green innovation initiatives. Moreover, Yu et. al. [22] found that dynamic supply chain complexity, characterized by factors such as market volatility and technological disruptions, also affects the ability of firms to adopt and sustain green practices. The integration of sustainable practices and the enhancement of resilience through adaptive measures pose challenges due to their inherent complexities [23]. It is imperative to comprehend the correlation between the intricacy of supply chains and the advancement of environmentally friendly innovation in order to enhance resilience. This is because strategic management assumes a central role in effectively addressing both structural and dynamic challenges [24–26]. Therefore, it is crucial to examine the effective implementation of green innovations in complex supply chain environments in order to foster the development of more sustainable and resilient supply chains.

The resource-based view (RBV), the dynamic capabilities theory, and the contingency theory are all put together to form a complete theoretical framework for making the supply chain more resilient through green innovation. The resource-based view (RBV) highlights the significance of distinct resources and capabilities, such as environmentally friendly strategies, in gaining a competitive edge and adaptability. It emphasizes the role of green innovation in enhancing supply chains. The dynamic capabilities theory provides a comprehensive analysis of how organizations adjust and restructure their competencies in order to effectively respond to environmental changes. This theory emphasizes the significance of green logistics in enhancing organizational resilience. contingency theory emphasizes the significance of organizational context in the effectiveness of green practices. According to this theory, competitive, technological, and environmental factors all have an impact on the strategic adoption of sustainability measures [27]. These theories clarify the crucial administration of resources, flexibility, and strategic congruence with contextual challenges as indispensable for cultivating a robust, environmentally friendly, and inventive supply chain system.

Bag et al. [28] emphasize the strategic significance of organizational resources and capabilities, specifically green innovation strategies, in attaining a competitive advantage and improving the resilience of supply chains and the effectiveness of logistics management. The dynamic capabilities theory serves as a valuable complement to the aforementioned concept by placing emphasis on the imperative for organizations to effectively adapt, integrate, and reconfigure in order to effectively respond to environmental changes. This theory underscores the significance of green logistics as a crucial factor in surmounting environmental challenges and enhancing overall resilience [29]. Contingency theory expands on the topic by suggesting that the effectiveness of green innovation and logistics in enhancing the resilience of the supply chain relies on the complex and ever-changing nature of the chain. It emphasizes the importance of aligning strategic resources with contextual factors in order to establish a resilient and sustainable system [30]. The aforementioned theories emphasize the significance of strategic resource management, adaptability, and contextual alignment in promoting a resilient and sustainable supply chain through green innovation, as illustrated in the conceptual model of our research (Figure 1). The conceptual research model of this study is designed to elucidate the intricate relationship between green innovation strategy, green logistics management practices, structural and dynamic supply chain complexity, and supply chain resilience [31]. At its core lies the independent variable of green innovation strategy, representing deliberate efforts by organizations to adopt environmentally friendly practices and technologies. This strategy is posited to positively influence both green logistics management practices and supply chain resilience [32]. Green logistics management practices, serving as the mediator in the model, encompass various initiatives aimed at reducing the environmental impact of logistical operations. It is hypothesized that these practices mediate the relationship between green innovation strategy and supply chain resilience, acting as a mechanism through which the implementation of green innovation strategies enhances the resilience of the supply chain [33]. Structural supply chain complexity, reflecting the intricacy and interdependence of supply chain components, and dynamic supply chain complexity, indicating the adaptability of the supply chain to external changes and disruptions, are considered moderators [34]. The conceptual model draws upon the RBV theory and DCT to provide theoretical underpinnings for understanding how green innovation contributes to the development of valuable resources and capabilities, and how organizations can adapt to dynamic environments to enhance supply chain resilience. Through the empirical validation of this framework, this study aims to contribute to both a theoretical understanding and practical insights for manufacturing firms in Turkey seeking to navigate the complexities of sustainability and resilience in their supply chains.

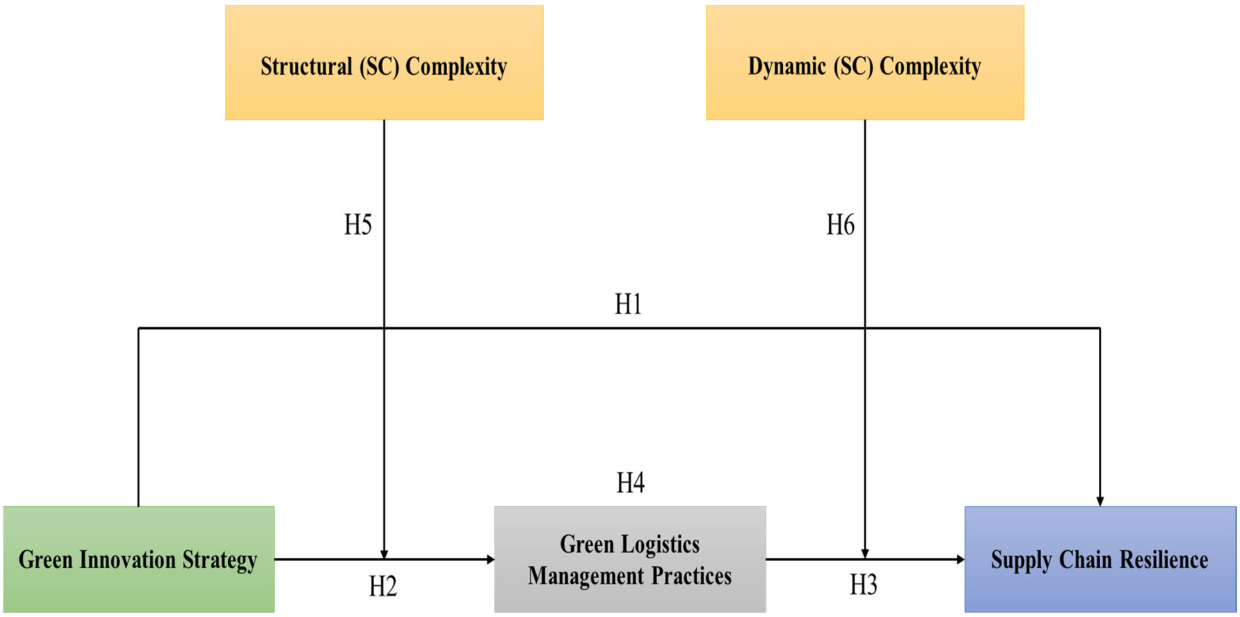

Figure 1. Research model.

This research contributes to the ongoing conversation surrounding green supply chain management (GSCM) by examining the interplay between green innovation strategies, logistics practices, and the complexity of supply chain operations. Drawing upon the findings of Liu and Wang [35] regarding the impact of green innovation on enhancing the performance of circular supply chains in times of economic uncertainty, this study aims to investigate the ways in which these strategies contribute to the reinforcement of resilience. This study emphasizes the value of teamwork in addressing supply chain challenges and incorporates research on eco-technological innovation by Nureen et al. [18]. The study conducted by Song et al. [10] provides additional insights into this investigation, highlighting the efficacy of platform-based strategies and technological advancements in promoting sustainable supply chain management. The authors emphasize the utilization of data-driven approaches and the significance of management factors within the platform economy.

The comprehension of the relationship between green innovation strategies and supply chain management has gained significant importance due to the growing urgency for sustainability in the global market [3]. The research by Hongquan and Abdullah [13] in the food industry and Mathu [2] in the context of triple-bottom-line approaches highlights the significance of eco-friendly logistics and innovation for sustainable performance and competitiveness. The primary objective of this study is to address a significant void in the existing body of literature by examining the impact of green practices on supply chain resilience. Specifically, this research aims to explore the mediating role of green logistics management practices and the moderating effect of structural and dynamic supply chain complexity. By conducting a comprehensive analysis of these factors, this study seeks to contribute to the development of a more sustainable and competitive business environment.

In accordance with scholarly endeavors to comprehend the influence of innovation on supply chains [3,36], the present study contributes to the scholarly conversation surrounding green innovation and the resilience of supply chains. To enhance the comprehension of how green innovation can enhance resilience within the Turkish manufacturing sector, this study utilizes the resource-based view (RBV), dynamic capabilities theory, and contingency theory. This study is motivated by the critical need to reconcile the imperatives within the manufacturing sector. As a major contributor to environmental pollution and resource consumption, manufacturing industries stand at the connection of sustainability efforts and supply chain resilience strategies [37]. The motivation starts from the recognition that while green innovation holds promise as a pathway to sustainability, its implications for supply chain resilience remain insufficiently understood. By probing this relationship, this research aims to provide actionable insights for firms striving to navigate the complex terrain of sustainable supply chain management. This study's primary challenge is understanding the interplay between green innovation and supply chain resilience. Despite growing recognition of the potential interaction between sustainability and resilience, empirical evidence regarding their relationship, particularly within the context of manufacturing firms, remains limited. This knowledge gap poses a barrier to informed decision-making and impedes progress towards sustainable and resilient supply chains. Previous research has explored green innovation and supply chain resilience as distinct phenomena. However, the integration of these two domains, and the mechanisms through which green innovation influences supply chain resilience, have received comparatively less attention [38]. Moreover, while studies have identified the importance of green logistics management practices in enhancing supply chain sustainability, their role in mediating the relationship between green innovation and supply chain resilience remains underexplored. This research seeks to address these gaps by examining the direct and mediated effects of green innovation on supply chain resilience, while also considering the moderating influence of structural and dynamic supply chain complexity. This paper proposes to investigate the pathways through which green innovation contributes to supply chain resilience, with a specific focus on manufacturing firms in Turkey. By empirically examining the relationships between green innovation, green logistics management practices, structural and dynamic supply chain complexity, and supply chain resilience, this research aims to advance theoretical understanding and offer practical insights for firms seeking to navigate the dual imperatives of sustainability and resilience. The objective of this study is to investigate and elucidate the strategic implementation of green innovation in handling the complexity of supply chains, providing valuable perspectives on sustainable competitive strategies in the face of environmental and operational challenges.

2. Theoretical Background and Hypotheses Development

2.1. Underpinning Theory

The resource-based view (RBV) is a crucial framework for examining the influence of green innovation on improving supply chain resilience and logistics. It emphasizes the significance of distinct resources in attaining a competitive edge [39]. According to Hart [40] and Russo and Fouts [41], it is argued that the implementation of green innovation strategies plays a vital role in enhancing the resilience of supply chains and managing green logistics. This, in turn, contributes to the promotion of environmental sustainability and the reinforcement of competitive advantage. Recent studies have confirmed the relevance of RBV in this field. Sahu et al. [42] demonstrated that implementing lean-green practices and green human resource management has a substantial positive impact on supply chain resilience. This highlights the importance of green innovation as a crucial resource. Zhaolei et al. [43] and Arda et al. [44] provide additional evidence in support of this claim by highlighting the significance of green supply chain management (GSCM) in promoting environmental sustainability and operational efficiency. They also underscore the strategic value of firm resources in fostering sustainability. Xiao et al. [45] further developed this concept by combining the resource-based view (RBV) with dynamic capability theory (DCT). They demonstrated that a deliberate emphasis on green innovation improves resilience and sustainability, highlighting the crucial role of RBV in tackling the complexities of contemporary markets and environmental sustainability through innovative approaches.

Teece et al.'s [46] theory of dynamic capabilities (DCT) emphasizes the significance of a company's ability to modify and restructure its resources in order to effectively respond to changing market circumstances. This underscores the theory's pertinence in attaining a competitive edge within dynamic contexts. Recent research has utilized the DCT in the context of green logistics and supply chain management, showcasing its effectiveness in promoting sustainability and enhancing competitive advantage. In their study, Xiao et al. [45] showed the connection between firms' strategic orientation towards green innovation and their capacity to build a long-lasting competitive advantage. Guo [47] conducted a study that examined the impact of green dynamic capabilities on environmental management and organizational performance. The findings of the study highlighted the importance of adaptability in order to effectively meet sustainability standards. According to Barakat et al. [48], dynamic capabilities play a crucial role in ensuring sustainability in supply chain clusters, making them indispensable for effective supply chain management. In addition, the study conducted by Li et al. [30] examined the relationship between green capabilities, digitalization, and supply chain management, emphasizing the importance of active capabilities in effectively tackling sustainability issues. These studies collectively validate the crucial significance of DCT in promoting the development of green logistics management practices and enhancing the resilience of supply chains. They demonstrate the practicality of the theory in effectively navigating the complex aspects of sustainable business practices.

Fiedler [49] introduced the contingency theory, which posits that the effectiveness of organizational strategies, particularly in the realm of sustainable supply chain management, is contingent upon their congruence with distinct external and internal contexts. The incorporation of green innovation strategies and logistics practices within the complex framework of supply chains is of utmost importance. Recent research supports the theory's applicability. In their study, Pham and Pham [50] emphasized the significance of leadership and learning in promoting green innovation. Zhaolei et al. [43] highlighted the need to adapt green supply chain practices to external and internal factors in order to achieve success in manufacturing. Parast [51] advocated for aligning resilience practices with specific environmental and organizational contexts to enhance supply chain performance. Lastly, Wang and Zhang [52] identified the complex interplay of motivations that influence the adoption of green supply chain practices. The aforementioned studies collectively support the premise of the contingency theory, which asserts that strategic decisions in sustainability are contingent upon the specific context. This highlights the importance of effectively managing the complexity and ever-changing nature of supply chains in order to attain resilience and sustainability.

The integration of the contingency theory with the resource-based view (RBV) and dynamic capabilities theory presents a comprehensive theoretical framework for analyzing the impact of green innovation strategies and logistics management practices on the resilience of supply chains. The aforementioned integrated approach underscores the imperative for organizations to effectively utilize their distinct resources and capabilities, adjust and restructure their operations in light of environmental challenges, and take into account the unpredictable nature of supply chain dynamics. The objective of our research is to enhance the domain of sustainable supply chain management by examining the complex connections among innovation, sustainability, and resilience. This will provide valuable knowledge regarding the opportunities and challenges that contribute to the development of supply chains with increased resilience.

2.2. Green Innovation Strategy

The concept of green innovation, which encompasses the creation of novel products, processes, and technologies with the objective of mitigating environmental damage and fostering sustainability, is progressively acknowledged as a crucial component in the pursuit of sustainable development objectives. Influential studies by Schiederig et al. [53], Rennings [54], and Horbach et al. [55] demonstrate the significance of the aforementioned concept in improving environmental performance and fostering economic growth. The efficacy of green innovation in enhancing operational efficiency, firm performance, and resilience in the context of environmental challenges is supported by empirical research [56,57].

Research conducted by Testa et al. [58] and Amores-Salvadó et al. [59] has demonstrated that the deliberate integration of green innovation into organizations, specifically in the manufacturing industry, can greatly improve both market competitiveness and sustainability. The arrangement of networks and the capacity to adapt to shifting environmental and regulatory requirements are just two examples of the complex interactions between organizational and operational elements within supply chains that shape improvement [60]. In addition, the effectiveness of green innovation strategies frequently relies on successful collaboration among partners within the supply chain. This collaboration is crucial for the convergence of resources and expertise, ultimately leading to the improvement of the environmental performance of the supply chain [61].

The significance of green innovation in effectively managing the complexities of sustainability and resilience is emphasized. The challenges are specifically addressed through collaborative efforts, as highlighted by Dangelico and Pujari [62] and Tseng et al. [63]. The COVID-19 pandemic has further emphasized the need for resilience in the face of global disruptions, emphasizing the urgency of transitioning to sustainable supply and production practices [64]. As a result, adopting green innovation strategies has become a fundamental aspect for companies, particularly in regions such as Turkey, intending to utilize environmental strategies to gain a competitive advantage in the international market.

2.3. Supply Chain Resilience

The importance of supply chain resilience in strategic management is being increasingly acknowledged due to its significance in effectively managing the complexities associated with green synergies. Resilience, as defined by Ponomarov and Holcomb [65] and Sheffi and Rice [66], refers to the ability to predict, adjust, and bounce back from disruptions. It is essential for ensuring the uninterrupted functioning of operations. Within the domain of green innovation, the interaction between structural and dynamic elements greatly improves the ability to withstand challenges, enabling a smooth shift from innovation to resilience.

To effectively address vulnerabilities, it is crucial to adopt a comprehensive perspective on resilience that encompasses both reactive and proactive strategies [67,68]. Incorporating environmentally friendly advancements, such as the practice of sustainable sourcing, assumes a crucial function within this framework, as it reduces environmental hazards and fosters sustainability principles. Gu et al. [69] underscore the importance of human capital in bolstering resilience, with a particular emphasis on implementing high-involvement human resource practices.

According to Brandon-Jones et al. [70] and Wieland and Wallenburg [71], dynamic capabilities, such as agility and adaptability, are crucial in effectively addressing unexpected challenges. According to Dubey et al. [72], the application of big data analytics highlights the significance of technological advancements in enhancing resilience.

The establishment of resilience is predicated upon the interplay between structural elements, such as network design, and dynamic elements, such as market responsiveness [73,74]. Effective collaboration and information sharing among partners facilitate the enhancement of supply chain visibility and coordination, thereby enabling a collective response to disruptions. Recent global challenges, such as the COVID-19 pandemic, have emphasized the importance of implementing resilient practices [75,76].

2.4. Green Innovation Strategy and Supply Chain Resilience

The field of strategic management is increasingly recognizing the crucial role played by green innovation strategies and supply chain resiliences (SCREs). This acknowledgement highlights the crucial importance of environmentally sustainable innovations, not only for the preservation of the environment but also for improving sustainable development. Based on the resource-based view (RBV), this perspective argues that having distinct resources and capabilities is crucial for gaining a competitive advantage and, consequently, being able to withstand disruptions [39].

The concept of green innovation strategy involves the development of innovative products, processes, and organizational practices with the goal of minimizing environmental harm and promoting sustainability. These strategies are postulated to have a positive influence on SCREs through various mechanisms. According to Hart and Dowell [77], the implementation of green innovations results in the optimization and reduction of waste, ultimately improving operational efficiency and flexibility. These factors are of utmost importance in ensuring resilience. Additionally, the implementation of environmentally sustainable practices has the potential to enhance a company's standing and relationships with stakeholders, thereby reinforcing the importance of supply chain collaborations in times of disruption [78]. According to Dangelico and Pujari [62], green innovation plays a crucial role in promoting organizational adaptability and learning, thereby enhancing firms' abilities to effectively address supply chain challenges.

Empirical studies substantiate theoretical frameworks. Dubey et al. [79] observed that companies possessing robust green innovation capabilities demonstrated greater proficiency in handling supply chain risks, owing to improved operational effectiveness and cooperative networks. Amui et al. [80] found that companies prioritizing green innovation demonstrated an increased ability to adapt to market and regulatory changes, establishing a connection between sustainability initiatives and strategic adaptability. Jelti et al. [81] observed that firms driven by green innovation that invest in renewable resources and technologies that are less reliant on limited resources decrease their susceptibility to fluctuations in commodity markets. This, in turn, helps to stabilize supply chains. In addition, Wiengarten et al. [82] contended that green innovations promote compliance with circular economy principles by reducing the negative effects of disruptions through the reuse and recycling of materials, thereby ensuring uninterrupted operations.

According to Kang et al. [83], organizational culture and innovation ambidexterity notably impact supply chain resilience and market performance. The study reveals that firms exhibit exceptional resilience and performance by engaging in explorative innovation. Shou et al. [84] highlighted the crucial significance of subjective norms in supply chains for implementing environmentally friendly innovation, thus improving supply chain resilience. The study by Xu et al. [85] investigated the influence of institutional pressures and cross-functional cooperation on green innovation in green supply chain management. The findings revealed a positive association between these pressures and cooperation, which in turn acts as a mediator in the relationship between pressures and green innovation.

According to Zhu and Sarkis [86], incorporating green innovation into supply chain management has been demonstrated to improve partner collaboration and information sharing. According to Tachizawa and Wong [68], this is particularly crucial for boosting resilience because it improves visibility and coordination throughout the supply chain. Given these insights, the following hypothesis is proposed.

H1: *The green innovation strategy exerts a positive influence on supply chain resilience.*

2.5. Green Innovation Strategy and Green Logistics Management Practices

The convergence of strategies for green innovation and practices for green logistics management holds significant importance within strategic management. This aligns with the resource-based view (RBV), which emphasizes the significance of unique resources and capabilities, such as green innovation, in sustaining a competitive edge (Barney). These strategies are crucial in enhancing environmental performance within logistics operations, signifying a notable transition towards sustainability.

Empirical evidence highlights the positive impact of green innovation on the adoption and efficacy of environmentally sustainable logistics practices. Singh and colleagues [87] emphasized how green technological advancements enhance the efficiency of logistics operations and mitigate carbon emissions. Li et al. [88] underscored the significance of green innovation in bolstering collaborative supply chain relationships, which is essential for the widespread adoption of sustainable logistics practices.

Further research highlights the significance of green innovation in integrating circular economy principles into logistics management, thereby facilitating the recycling and reuse of resources [24]. In their study, Kapoor and Dwivedi [89] demonstrated the role of green innovation strategies in facilitating the growth of logistics operations that are resilient and adaptable, enabling them to address changes in the environment and market conditions effectively. In addition, the progress of digital green technologies, including blockchain and IoT, has emerged as a noteworthy element in enhancing transparency and efficiency in logistics [90].

The study by Zhang et al. [36] revealed disparities in green innovation practices within the logistics industry, emphasizing areas that have demonstrated commendable sustainability initiatives and the significance of green innovation in promoting regional logistics sustainability. Xiao et al. [90] emphasized the significant impact of governmental assistance in promoting green innovation in logistics, highlighting the indispensability of policy incentives in cultivating sustainable logistics practices. Additionally, Xu et al. [85] and Wang et al. [91] examined the influence of institutional pressures and innovation capabilities on green logistics practices. Their research revealed that implementing internal and external collaborative initiatives, supported by cross-functional cooperation, leads to notable enhancements in the sustainability and efficiency of logistics operations. Given this backdrop, it is hypothesized that:

H2: *The green innovation strategy positively affects green logistics management practices.*

2.6. Green Logistics Management Practices and Supply Chain Resilience

According to Barney [39], the resource-based view (RBV) theory suggests that utilizing distinctive resources and capabilities, such as environmentally sustainable logistics practices, is crucial in attaining a competitive edge and bolstering the resilience of supply chains. The role of sustainable transportation and warehousing in promoting a resilient supply chain is crucial due to their ability to minimize environmental impact and optimize resource utilization [66,92].

Empirical evidence supports the positive impact of green logistics management on supply chain resilience. Research conducted by Dubey et al. [93] provides evidence that companies possessing sophisticated green logistics capabilities demonstrate enhanced resilience in the face of disruptions by implementing sustainable operational frameworks. According to Choi and Hwang [94], environmental management practices significantly enhance resilience by facilitating ongoing improvement and innovation.

Furthermore, implementing environmentally friendly logistics practices is crucial to strengthening the relationship between supply chain partners and facilitating the exchange of valuable information and resources essential for overall resilience [95,96]. According to Chowdhury and Quaddus [97], these practices enhance risk management endeavors, assisting organizations in more effectively predicting and minimizing potential disruptions.

Recent research consistently confirms the correlation between environmentally friendly logistics practices and the ability of supply chains to withstand challenges. Ivanov [76] emphasizes the significance of sustainable supply chain practices, such as green logistics, in maintaining operational continuity during times of crisis. With the help of risk management and analytics, Liu and Wei [98] show how supply chains focused on disruption can significantly improve resilience. According to Ahmad et al. [99], the authors emphasize the significant impact of green supply chain management (GSCM) practices on sustainable performance, thereby emphasizing the operational benefits associated with environmental strategies.

In addition, Afzal and Hanif [100] note that green supply chain initiatives, excluding green purchasing, positively impact firm performance, highlighting the significance of environmental practices. Ullah et al. [101] demonstrate that implementing green supply chain management (GSCM) practices allowed companies to recover from economic downturns caused by the COVID-19 pandemic, highlighting the advantageous resilience of green practices. The studies by Wiredu et al. [102] and Akani et al. [103] add to what is already known by showing that using environmentally friendly methods not only improves a company's environmental performance and competitive edge, but also makes the company more resilient by making marketing more effective and strengthening its brand image. This hypothesis is formulated and tested to examine the relationship between green logistics management practices and supply chain resilience. Grounded in theoretical frameworks like the resource-based view and dynamic capability theory, it addresses the growing importance of sustainability in logistics. By exploring how environmentally sustainable practices influence the resilience of supply chains, the hypothesis bridges the gap between green initiatives and operational resilience. It suggests that investments in green logistics not only benefit the environment but also enhance a supply chain's ability to withstand disruptions, offering insights for strategic decision-making and policy formulation. Testing this hypothesis contributes to both theoretical advancement and practical implications in the field of supply chain management, thereby validating the following hypothesis.

H3: *Green logistics management practices positively affect supply chain resilience.*

2.7. Green Logistics Management Practices as a Mediator

Green innovation strategies are essential for companies aiming to gain a competitive edge in the environmentally conscious market, as they are based on sustainable development and environmental stewardship [40,41]. Teece, Pisano, and Shuen [46] introduced the dynamic capabilities theory, focusing on an organization's capacity to adapt and renew its competences to respond effectively to changing environments. This theory underscores the importance of a firm's internal and external organizational skills, resources, and functional competences in maintaining a competitive advantage amidst rapid technological and market changes. This theory underscores the significance of promptly reorganizing resources and operations in response to shifts in the external environment. The implementation of green innovation strategies within the supply chain is facilitated by adopting green logistics management practices, including sustainable transportation, warehousing, and material handling [104].

Extensive documentation exists regarding the mediating role of green logistics management practices in translating green innovation strategies into significant enhancements in supply chain resilience. Studies conducted by Pagell and Wu [105] and Ageron et al. [106] demonstrate that incorporating environmental factors into logistics operations significantly enhances the supply chain's flexibility and adaptability, thus strengthening its resilience.

Further research conducted by Wiengarten et al. [82] demonstrates that companies prioritizing green logistics management attain exceptional environmental outcomes and strengthen their capacity to navigate and rebound from disruptions effectively. Beske et al. [107] observed that these practices play a crucial role in promoting collaborative networks, subsequently enhancing supply chains' resilience and flexibility.

Continuing research provides additional evidence to support the crucial role of green logistics practices in mediating the issue. Liu and Wei [98] demonstrate how supply chain risk management analytics enables organizations to quickly adjust to disruptions, which aligns with the dynamic capabilities theory's focus on strategically reconfiguring in response to environmental changes. The studies by Ahmad et al. [99] and Afzal and Hanif [100] look at how green supply chain management (GSCM) practices can help turn green innovation strategies into better long-term and overall firm performance.

Lin et al. [108] examine the adoption of green supply chain management (GSCM) among small and medium enterprises (SMEs), demonstrating how GSCM practices result in both environmental and economic advantages, with a particular focus on SMEs. Asamoah et al. [109] look into how green absorptive capacity can be used as a mediating variable to make green supply chain management (GSCM) practices have a bigger effect on how well a company does. The authors propose that the integration and implementation of green innovations play a vital role in optimizing the advantages of GSCM. Wiredu et al. [103] stress that green supply chain management (GSCM) practices play a crucial role in improving both environmental performance and competitive advantage, which in turn makes supply chains more resilient. Given this comprehensive body of empirical evidence, it is hypothesized that:

H4: *Green logistics management practices mediate the relationship between green innovation strategy and supply chain resilience, such that the implementation of green innovation strategies leads to improved green logistics management practices, which in turn enhance the resilience of the supply chain.*

2.8. Structural Supply Chain (SC) Complexity as a Moderator

According to Donaldson [110], contingency theory suggests that the efficacy of organizational strategies is greatly impacted by the attributes of both the internal and external contexts in which they are implemented. In this theoretical framework, we propose that the complexity of the structural supply chain plays a crucial role in moderating the effectiveness of green innovation strategies in improving green logistics management practices.

According to Pant et al. [111], the complexity of a structural supply chain can be characterized by several dimensions, such as the extent of supplier networks, geographical distribution, product variety, and the level of interdependencies among supply chain entities. The impact of such complexity on supply chain performance and strategic management is widely recognized. The study by Bode and Wagner [112] emphasizes the significance of structural factors in influencing the complexity of supply chains, which may have implications for disruptions. Simultaneously, Aitken et al. [113] advocate for a thorough analysis of complexity to develop strategies that reduce or overcome its impacts, emphasizing the significance of comprehending these complexities for efficient supply chain management.

The central focus of this hypothesis revolves around the correlation between the green innovation strategy and green logistics management practices, which are crucial for promoting sustainability within supply chains. According to Zhang et al. [36], green innovation strategies encompass implementing various processes, products, and technologies to reduce the environmental consequences associated with supply chain operations. On the other hand, Trivellas et al. [114] assert that green logistics management practices are designed to enhance environmental performance by optimizing logistics and transportation processes. According to our hypothesis, the complexity of the structural supply chain affects the relationship, with less complex supply chains showing a stronger impact. Less complex supply chains need more coordination challenges and decision-making clarity. De Stefano and Montes-Sancho [115] argue that structural complexity significantly influences greenhouse gas (GHG) emissions through supply chains. They suggest that simpler supply chains facilitate the successful implementation of green innovations by promoting clearer communication and reducing interdependencies. This represents the level of complexity inherent in the firm's supply chain network, including factors such as the number of suppliers, the diversity of products, and the complexity of distribution channels [116].

There is also a split in the research literature about the link between supply chain complexity and performance. It suggests that the effect of supply chain complexity depends on the management strategies used [117]. According to Memiş [118], less complex supply chains are believed to offer a more conducive setting for implementing sustainable practices within the realm of green innovation and logistics management. This is attributed to their inherent flexibility and adaptability. On the other hand, more complex supply chains may require advanced, data-oriented methods to implement green strategies successfully. This is supported by Iftikhar et al. [119], who emphasized the role of big data analytics in managing the complexities of supply chains. Based on the aforementioned theoretical and empirical foundations, we propose the following hypothesis for further investigation:

H5: *Structural supply chain (SC) complexity moderates the relationship between the green innovation strategy and green logistics management practices, such that the relationship is stronger in less structurally complex supply chains.*

2.9. Dynamic Supply Chain (SC) Complexity as a Moderator

According to Donaldson [110], contingency theory provides a comprehensive understanding that the effectiveness of management strategies is closely tied to the particular operational contexts, encompassing both internal and external factors, within which an organization operates. Christopher and Lee [120] contend that the complex structural complexities and the ever-changing environmental conditions inherent in supply chains necessitate management strategies that are agile and adaptive, ensuring long-lasting resilience and sustainability. Within this theoretical framework, the adoption of green logistics management practices emerges as pivotal for enhancing supply chain performance and sustainability. These practices, characterized by eco-friendly transportation, packaging, and warehousing systems, play a vital role in aligning supply chain operations with sustainability objectives while bolstering resilience to external disruptions. According to Srivastava [104] and Linton et al. [121], these practices involve deliberately incorporating environmental factors into logistics and supply chain operations to reduce ecological impacts and foster sustainable results.

Empirical research [105,122] has supported the significance of green logistics management practices, such as reducing energy consumption, minimizing waste, and improving operational efficiency, in enhancing environmental performance and strengthening supply chain resilience. Implementing such practices not only supports the overall sustainability objectives but also significantly improves the ability of supply chains to withstand potential disruptions, thus playing a crucial role in building resilient supply chain structures [123].

The dynamic supply chain complexity concept, which encompasses the inherent volatility and unpredictability in supply chain environments, has a significant impact on the interaction between green logistics management practices and supply chain resilience [70,73]. It is hypothesized that in settings with lower levels of dynamic complexity, the predictability of operations significantly supports the successful implementation of green logistics strategies. This, in turn, enhances resilience by improving risk management, operational efficiency, and sustainability performance. On the other hand, supply chains characterized by a significant level of dynamic complexity face the difficulties presented by swift changes and uncertainties. As a result, they must implement more agile and responsive strategies to maintain their resilience [66,74].

In addition, the academic literature emphasizes the role of supply chain complexity in influencing the effectiveness of strategies designed to enhance resilience [65,120]. Supply chains characterized by lower levels of complexity are considered more favorable for successfully adopting green logistics practices. This is because such supply chains naturally facilitate improved coordination, efficient information exchange, and the strategic alignment of sustainability goals among stakeholders within the supply chain. Consequently, it is hypothesized that:

H6: *Dynamic supply chain (SC) complexity moderates the relationship between green logistics management practices and supply chain resilience, such that the relationship is stronger in less dynamic complex supply chains.*

3. Method

3.1. Data Collection and Sampling

This study uses a quantitative design method to examine the study's integrated theoretical model. Data were collected through the use of a questionnaire survey. The survey participants were managers of manufacturing companies listed in the Trade Gazette of Turkey [124] in Istanbul and Izmir, Turkey. The managers were selected based on their substantial experience and knowledge in the domain of supply chain management. These individuals occupy key positions within their organizations that directly influence or are involved in the planning, implementation, and monitoring of supply chain activities. Their roles span across various aspects of supply chain management, including but not limited to logistics, procurement, production planning, and supply chain strategy development. The purposive sampling technique [125] (Al Tera et. al., 2024) was adopted for data collection. Before data collection, one of the authors called the sampled firms to explain the purpose of the research and sought their voluntary participation. The majority of the sampled firms accepted our invitation, while some declined to be involved in the survey. The survey was administered physically and electronically. A brief explanation of the research was sent together with the guarantee of confidentiality of the responses. It was requested that the respondent send back the questionnaire within two weeks. Data collection took place from August 2023 to December 2023. A total of 651 questionnaire surveys were sent out, and 412 managers participated and returned the survey. A total of 8 questionnaires were either incorrectly filled or not totally completed. Therefore, 404 complete/valid questionnaires were returned, leading to a response rate of 62.06%.

Information regarding the sample is displayed in Table 1. In terms of firm age (years), between 1 and 10, there were 91 (22.52%), 11–19, 183 (45.30%), and above 20, 130 (32.18%). Based on industry, food and beverages account for 105 (25.99%), textile and building materials manufacturing 129 (31.93), wood and furniture manufacturing 74 (18.33%), paper and printing industry 63 (15.59%), medicine manufacturing 19 (4.71%) and others 14 (3.45%). In terms of firm size (number of employees), less than 50 account for 158 (39.11%), between 51 and 100, 197 (48.76%), and above 100, 49 (12.13%).

Table 1. Sample information.

Characteristics (n = 404)	**Category**	**Frequency**	**%**
Firm age (years)			
	Between 1 and 10	91	22.52
	11–19	183	45.30
	Above 20	130	32.18
Industry	Food and beverages manufacuring	105	25.99
	Textile and building materials manufacturing	129	31.93
	Wood and furniture manufacturing	74	18.33
	Paper and priniting industry	63	15.59
	Medicine manufacturing	19	4.71
	Others	14	3.45

Table 1. *Cont.*

Characteristics (n = 404)	Category	Frequency	%
Firm size (employee number)	Less than 50	158	39.11
	Between 51 and 100	197	48.76
	Above 100	49	12.13

3.2. Measurement

In operationalizing the constructs for this study, a variety of measurement items were utilized, as detailed in Appendix A, Table A1. The green innovation strategy was measured with 7 items adopted from [126,127]. The measurement of this construct was conducted using indicators that evaluate the degree to which companies have integrated environmental considerations into their operations and business practices. These indicators encompass a broad spectrum of green innovation activities, ranging from implementing changes in business practices to minimize the environmental impact to embracing cleaner energy sources. The choice of these indicators was influenced by the necessity to cover a wide range of actions that make up green innovation in the manufacturing industry. These indicators encompass both product and process innovations that directly contribute to environmental sustainability.

Green logistics management practices were measured with 4 items adopted from [128–130]. The indicators for this construct assess the execution of ecologically sustainable logistics and supply chain practices. These encompass reverse logistics, eco-friendly training and policies, and the utilization of sustainable transportation and packaging. The selection of these indicators is determined by their recognized importance in improving the environmental efficiency of supply chains as well as their ability to facilitate the implementation of green innovation strategies into practical logistics operations. Structural supply chain complexity was measured with 3 items adopted from [112,131]. Dynamic supply chain complexity was measured with 3 items adopted from [70,131]. The measurement of these constructs involved the use of indicators that assessed both the structural and dynamic aspects of supply chain complexity. These indicators included the number of suppliers, customer demands, and the variability in lead times. The choice of these indicators was influenced by the existing body of knowledge on supply chain management, which highlights the significance of comprehending both the unchanging and dynamic elements of supply chain structures and how they affect the efficiency of environmentally friendly practices. Supply chain resilience was measured with 4 items adopted from [132,133]. All items were rated on a 7-point likert scale from 1 = strongly disagree to 7 = strongly agree. Indicators for this construct evaluate the capacity of companies to effectively handle disruptions, retain authority over supply chain operations, and execute alternative strategies. The selected indicators were designed to encompass the various aspects of resilience within the framework of green supply chains. They aim to measure both the ability to endure environmental disruptions and the strategic flexibility to address new challenges.

3.3. Non-Response Bias and Common Method Bias

We examine non-response by computing the mean differences between early and late participants for each construct through the t-test. The absence of significant differences in the results obtained indicates that non-response bias is not a serious concern in the current study. Further, CMB could pose an issue since this study collected data from single respondents. To resolve this, we adhered to several procedures recommended in the literature. Firstly, to promote honest responses from the survey participants, we randomized the order of the questionnaire items and assured them of the anonymity of their responses. Secondly, Harman's single-factor test was utilized to detect common method bias following the suggestions of Podsakoff et al. [134]. After inputting all the items, a principal component analysis (PCA) was conducted, leading to 5 factors with eigenvalues higher than 1. The overall variance was 59.83%, with the first factor explaining only 27.73%. Thirdly, a confirmatory factor analysis was conducted where all the measurement items were regressed on a single factor (i.e., common latent factor) to examine CMB. The results indicated that the common latent factor (i.e., one-factor model) had poorer model fit indices (χ^2/df = 8.334 RMSEA = 0.129, CFI = 0.643, IFI = 0.644, TLI = 0.657, NFI = 0.640, AGFI = 0.419, GFI = 0.498). Hence, CMB does not appear to be a serious concern in the current study.

3.4. Measurement Model

The reliability and validity of the measures were computed through a confirmatory factor analysis (CFA) in AMOS 20. Cronbach's alpha (α) and composite reliability (CR) were used to assess the reliability of the measures. Convergent and discriminant validity were used for the validity of the model. Table 2 shows that CR (0.865 to 0.959) and α (0.883 to 0.958) values were above the recommended cut-off of 0.7 for all the five constructs of the study, indicating sufficient reliability. Table 2 and Figure 2 show that standardized factor loadings for all items were above 0.7 (0.754 to 0.947), showing excellent construct validity [135]. To examine convergent validity, each item was linked with the related variable, and the covariance between the variables was freely evaluated. As illustrated in Table 2, the results of the model fit indices for the study's conceptual model show an excellent fit (χ^2/df = 2.212, RMSEA = 0.05, CFI = 0.974, IFI = 0.974, TLI = 0.969, NFI = 0.953, AGFI = 0.885, GFI = 0.912), showing evidence of convergent validity [136]. In addition, as demonstrated in Table 2, the AVE values for all variables were above 0.5 (0.616 to 0.865), showing further evidence of convergent validity [137].

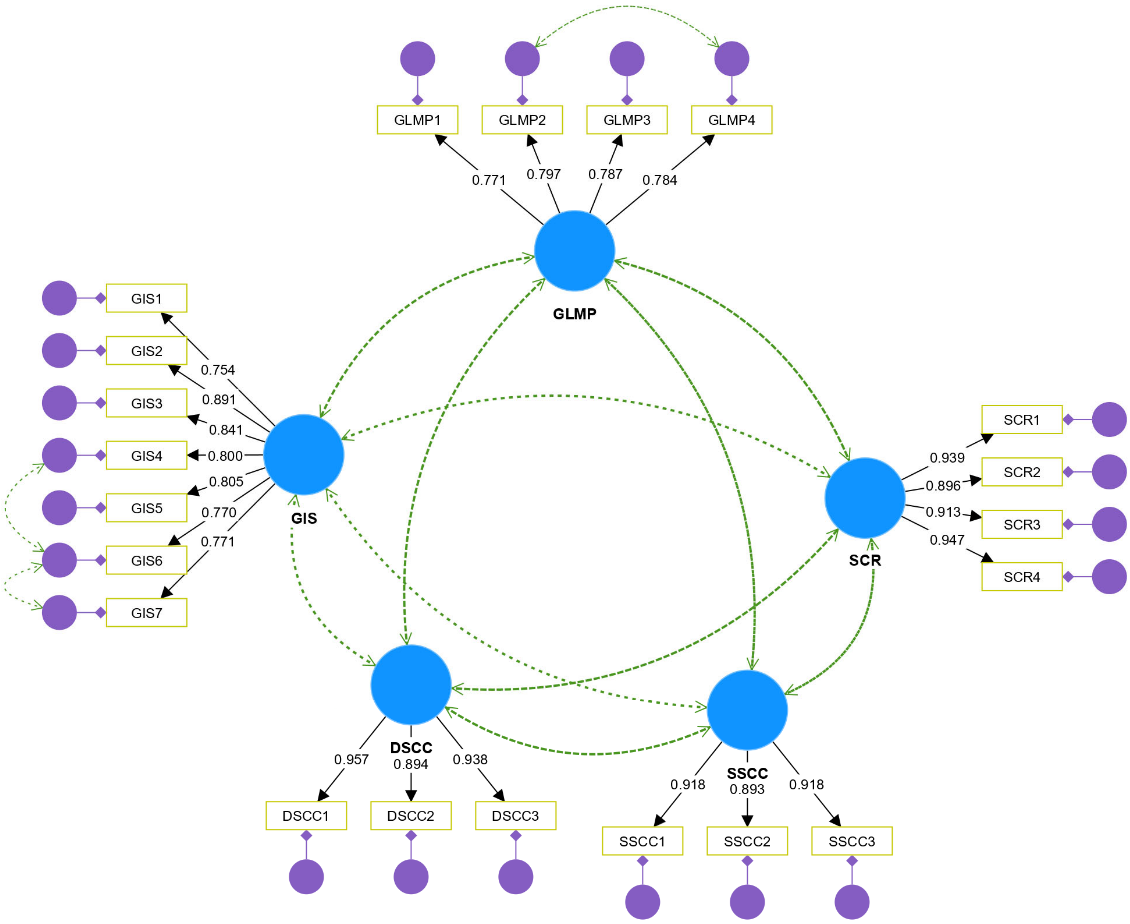

Figure 2. Measurement items' standardized estimates.

Table 2. Estimation of reliability and validity.

Variable	Item Codes	Loadings	Cronbach's Alpha	Composite Reliability	Average Variance Extracted
Green innovation strategy			0.931	0.928	0.649
	GIS1	0.754			
	GIS2	0.891			
	GIS3	0.841			
	GIS4	0.800			
	GIS5	0.805			
	GIS6	0.770			
	GIS7	0.771			
Green logistics management practices			0.883	0.865	0.616
	GLMP1	0.771			
	GLMP2	0.797			
	GLMP3	0.787			
	GLMP4	0.784			
Structural supply chain complexity			0.934	0.935	0.828
	SSCC1	0.918			
	SSCC2	0.893			
	SSCC3	0.918			
Dynamic supply chain complexity			0.949	0.950	0.865
	DSCC1	0.957			
	DSCC2	0.894			
	DSCC3	0.938			
Supply chain resilience			0.958	0.959	0.854
	SCR1	0.939			
	SCR2	0.896			
	SCR3	0.916			
	SCR4	0.947			
Model fit indices: χ^2/df = 2.212, RMSEA = 0.05, CFI = 0.974, IFI = 0.974, TLI = 0.969, NFI = 0.953, AGFI = 0.885, GFI = 0.912					

Note: GIS = green innovation strategy, structural supply chain complexity = SSCC, DSCC = dynamic supply chain complexity, GLMP = green logistics management practices, SCR = supply chain resilience.

Furthermore, following Fornell and Larcker [138], we calculated the square root of AVE (demonstrated in Table 3) to assess discriminant validity. The results indicate that the square root of AVEs is greater than the nearby correlation coefficient. Hence, discriminant validity is ensured in this study.

Table 3. Descriptive statistics and discriminant validity (Fornell–Larcker).

Variable	Mean	Standard Deviation	GIS	GLMP	SSCC	DSCC	SCR
GIS	4.825	1.435	**0.806**				
GLMP	4.859	1.301	0.654 **	**0.784**			
SSCC	4.713	1.282	0.299 **	0.434 **	**0.910**		
DSCC	5.439	1.951	0.338 **	0.395 **	0.494 **	**0.930**	
SCR	4.817	1.631	0.429 **	0.310 **	0.377 **	0.458 **	**0.979**

Note: ** signifies correlation is significant at 0.01 level, bold values in diagonal are square root of AVEs.

4. Results of Data Analysis

4.1. Test of Direct and Mediation (Indirect)

Model 4 in Hayes' PROCESS plug-in was used to test the direct and mediating effect. Following Baron and Kenny's [139] multiple steps approach, hypotheses H1–H4 were examined. Table 3 shows the results from the test of the direct and indirect effects. First, the green innovation strategy has a positive effect on supply chain resilience (Coeff. = 0.331, t = 6.207, $p < 0.001$). Second, the green innovation strategy has a positive effect on green logistics management practices (Coeff. = 0.774, t = 32.856, $p < 0.001$). Green logistics management practices have a positive effect on supply chain resilience (Coeff. = 0.458, t = 7.654, $p < 0.001$). The three positive direct significant effects validate H1, H2, and H3.

In line with Baron and Kenny [138], with the inclusion of green logistics management practices, the direct relationship between the green innovation strategy and supply chain resilience remains significant. This result indicates that green logistics management practices partially mediate the relationship [138,139]. We utilized the 95% bias-corrected bootstrapping method with 5000 resamples to further confirm the significant indirect effect. The bootstrap technique has been used because it comprehensively conceptualizes indirect effects [125,140,141]. A mediation effect is established if zero does not lie between the confidence intervals. Table 4 shows the results of the indirect effect (Coeff. = 0.665, BootSE = 0.098, BootLLCI = 0.476, BootULCI = 0.862). Since the bootstrap confidence interval did not contain zero, the indirect effect of the green innovation strategy on supply chain resilience through green logistics management practices is confirmed, validating H4.

Table 4. Testing of direct effects and mediation hypotheses.

	Outcome: Green Logistics Managements				Outcome: Supply Chain Resilience Practices			
	Model 1				Model 2			
	Coeff.	S.E.	t	95% CI	Coeff.	S.E.	t	95% CI
Green innovation strategy	0.774	0.024	32.856 ***	[0.728, 0.820]	0.331	0.030	6.207 ***	[0.431, 0.831]
Green logistics management practices					0.458	0.031	7.654 ***	[0.638, 0.892]
The indirect effect of green innovation strategy on supply chain resilence through green logistics management (5000 resamples)								
	Coeff	BootSE	BootLLCI	BootULCI				
	0.665	0.098	0.476	0.862				

Note: *** signifies correlation is significant at 0.001 level

In addressing the potential influences of firm size and industry type on our model, these variables were initially included as controls within our regression analyses to assess their impact on the relationships between green innovation strategies, green logistics management practices, and supply chain resilience. Our analytical approach was based on a robust multivariate regression framework, where firm size and industry type were tested for their statistical significance and effect sizes.

Despite expectations from the existing literature suggesting that industry characteristics should impact supply chain dynamics [142], in our analysis, these factors did not exhibit significant effects on the model's outcomes. This lack of significance was consistently observed across multiple model specifications, including both interaction and direct-effects analyses. The *p*-values associated with these variables exceeded the conventional threshold for significance (0.05), indicating that within the context of our data and specific to the manufacturing sectors examined, the variations in firm size and industry type did not materially influence the core relationships tested in our study.

These findings suggest a possible industry homogeneity in terms of green innovation adoption and its effects, or that other factors such as company-specific strategies or external environmental pressures might play a more pivotal role in driving supply chain resilience than the generic characteristics of firm size and industry type.

4.2. Testing of Conditional Effect (Moderated Mediation)

Table 5 shows the results for the conditional direct effects. To test these conditional direct effects, Model 21 in Hayes' PROCESS tool was employed. The green innovation strategy positively and significantly predicts green logistics management practices (Coeff. = 0.739, t = 29.690, $p < 0.001$, 95% CI [0.690, 0.788]) in Step 1. Structural supply chain complexity moderates this direct effect (Coeff. = 0.054, t = 2.918, $p < 0.05$, 95% CI [0.018, 0.091]). The simple slope test was employed to further probe the conditional direct effect. Table 5 displays the conditional direct effect. The outcome of the simple slope test reveals the conditional direct effect of the green innovation strategy on green logistics management practices when the moderator (structural supply chain complexity) is at different levels (i.e., +1SD above the mean, mean, and −1SD below the mean). At low structural supply chain complexity, the effect of the green innovation strategy on green logistics management practices was stronger (Coeff. = 0.808, t = 29.689, $p < 0.001$, 95% CI [0.753, 0.865]). In contrast, at high structural supply chain complexity, the relationship was weaker (Coeff. = 0.670, t = 16.964, $p < 0.001$, 95% CI [0.592, 0.747]). The graphical visualization demonstrated in Figure 3 validates H5.

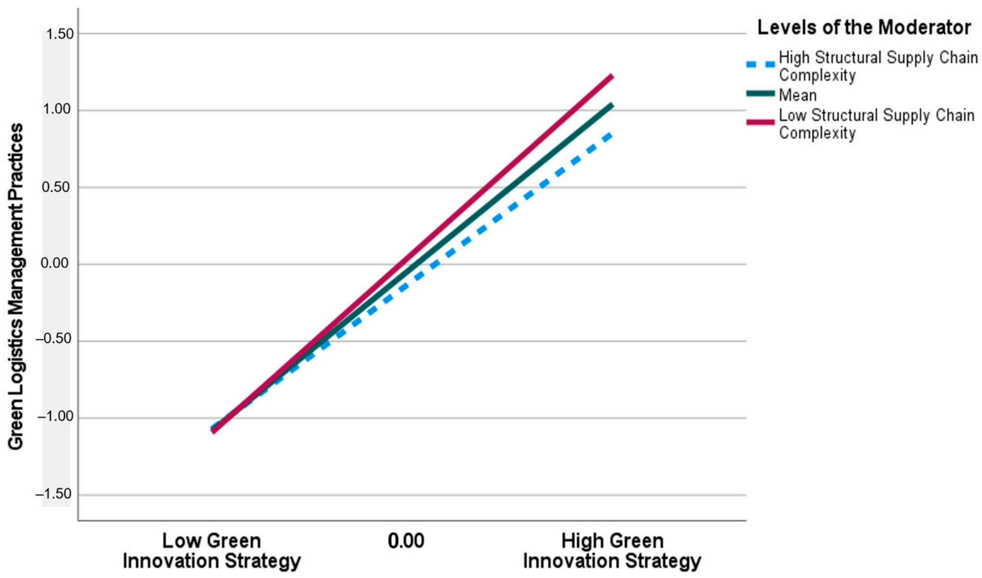

Figure 3. Structural supply chain complexity moderating the relationship between green innovation strategy and green logistics management practices.

Table 5. Testing of moderated mediation hypotheses.

Step 1: Mediator = Green Logistic Management Practices	**Coeff.**	**SE**	**t**	**95% CI**	
				Lower	**Upper**
Constant	−0.019	0.034	−0.587 (ns)	−0.087	0.047
Green innovation strategy	0.739	0.025	29.690 ***	0.690	0.788
Structural supply chain complexity	0.069	0.027	2.603 *	0.017	0.121
Green innovation strategy × structural supply chain complexity	0.054	0.019	2.918 *	0.018	0.091
R^2			0.738 **		
The conditional direct effect of green innovation strategy on green logistic management practices					
−1SD (Low)	0.808	0.028	29.689 ***	0.753	0.865
Mean	0.739	0.024	28.266 ***	0.690	0.788
+1SD (High)	0.670	0.039	16.964 ***	0.592	0.747
Step 2: Outcome = Supply chain resilience					
Constant	4.789	0.074	64.667 ***	4.643	4.936
Green innovation strategy	0.623	0.092	6.775 ***	0.443	0.805
Green logistics management practices	0.638	0.091	6.164 ***	0.434	0.842
Dynamic supply chain complexity	0.360	0.039	9.035 ***	0.282	0.438
Green logistic management practices × dynamic supply chain complexity	0.067	0.028	3.106 *	0.027	0.112
R^2	0.744 ***				
The conditional direct effect of green logistic management practices on supply chain resilience					
−1SD (Low)	0.516	0.039	9.976	0.441	0.680
Mean	0.259	0.044	4.201 ***	0.149	0.291
+1SD (High)	0.177	0.048	2.996 ***	0.086	0.122
Index of moderated mediation					
	Index	BootSE		BootLLCI	BootULCI
	0.015	0.017		0.002	0.055
Indices of conditional moderated mediation by structural supply chain complexity					
	Index	BootSE		BootLLCI	BootULCI
	0.031	0.015		0.003	0.063
	0.034	0.015		0.004	0.065
	0.037	0.016		0.005	0.070

Note: * signifies correlation is significant at 0.05 level, ** signifies correlation is significant at 0.01 level, *** signifies correlation is significant at 0.001 level

Considerations and Limitations of Analytical Tools

Although Hayes's PROCESS tool has greatly aided our comprehension of the impacts and interconnections within our model, it is crucial to recognize the specific constraints linked to its usage. First and foremost, the PROCESS method is based on the assumption that there are linear relationships between variables. However, this assumption may not always accurately represent the intricate interactions that occur in real-world data [143]. This may result in overly simplistic interpretations of the mediating or moderating effects that we have previously discussed.

In addition, the PROCESS method does not automatically consider the possibility of multicollinearity between predictor variables. This can impact the reliability of the interaction terms and their significance in the regression models [144]. Researchers are required to manually examine multicollinearity and ensure that the variables included in the model do not excessively impact one another.

Another factor to take into account is the tool's dependence on bootstrap methods for producing confidence intervals and conducting significance testing. This assumes that the sample accurately reflects the population. These issues can arise when the sample is not a true reflection of the population or when the data do not follow a normal distribution, which can result in inaccurate estimates [145].

Although PROCESS has limitations, it remains a potent analytical tool when used with an awareness of its constraints and in combination with thorough data diagnostics. It is advisable for future research to take into account these factors in order to improve the strength and clarity of their findings.

Similarly, green logistics supply chain management practices have a positive effect on supply chain resilience (Coeff. = 0.638, t = 6.164, $p < 0.001$, 95% CI [0.434, 0.842]) in Step 2. Dynamic supply chain complexity moderates this direct effect (Coeff. = 0.067, t = 3.106, $p < 0.05$, 95% CI [0.027, 0.112]). The simple slope test shows that at low dynamic supply chain complexity, the effect of green logistics management practices on supply chain resilience was stronger (Coeff. = 0.516, t = 9.976, $p < 0.001$, 95% CI [0.441, 0.680]). In contrast, at high dynamic supply chain complexity, the relationship was weaker (Coeff. = 0.177, t = 2.918, $p < 0.001$, 95% CI [0.086, 0.122]). The graphical visualization demonstrated in Figure 4 validates H6. Furthermore, the index of moderation mediation was significant (index = 0.015, SE = 0.017, CI [0.002, 0.055]).

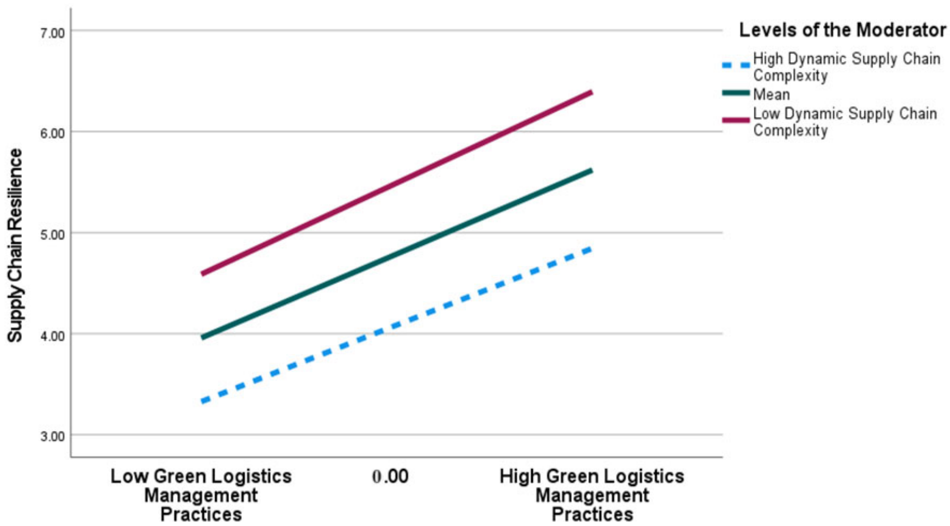

Figure 4. Dynamic supply chain complexity moderating the relationship between green logistics management practices and supply chain resilience.

5. Discussion

Analyzing the relationship between green innovation strategies and supply chain resilience has produced strong evidence supporting the hypothesis that implementing these strategies greatly strengthens supply chain resilience. The statement presented is not only statistically significant but also firmly grounded in the resource-based view (RBV) theoretical framework, as Barney [39] expounded. The RBV prioritizes the utilization of internal resources to gain a competitive edge. The research by Ye and Lau [3] and Jantapoon and Saenchaiyathon [146] emphasizes the significance of strategic foresight, collaboration, and innovation in enhancing supply chain resilience. The authors Okogwu et al. [147] provide evidence to support the notion that integrating sustainability into corporate strategies yields advantageous outcomes. Liu [148] examines the integration of low-carbon practices with e-commerce using big data analytics, drawing parallels to the research conducted by Setiawan et al. [23] on integrating digitalization and green supply chains. The study demonstrates that implementing digital and green initiatives enhances the resilience of supply chains, thereby aligning with the resource-based view (RBV) framework.

The empirical research provides strong evidence that green innovation strategies improve the resilience of supply chains and the management of logistics. This aligns with the resource-based view (RBV), which emphasizes the importance of internal resources in gaining a competitive advantage. In the face of policy uncertainties, Liu and Wang's research [35] demonstrates the role of green innovation in fostering circularity. Similarly, Nikseresht et al. [149] and Hongquan and Abdullah [13] have demonstrated the beneficial effects of green innovation on sustainable logistics and green supply chain management (GSCM) practices, such as green procurement. The study by Allahham et al. [150] investigates the impact of incorporating big data analytics and artificial intelligence (AI) on the sustainability of hospital supply chains in the United Kingdom. The authors emphasize the significance of technology in enhancing logistics efficiency and resilience. The collective findings of this study confirm the strategic importance of green innovation in attaining sustainability and operational excellence within logistics management.

Current academic research strongly advocates for the incorporation of green logistics management practices as strategic assets that are essential for improving the resilience of supply chains. This approach is based on the resource-based view (RBV). Implementing these practices is crucial to addressing environmental challenges and enhancing the resilience and flexibility of supply chains. Raffington and Adesiyan [151] and Pranee et al. [152] presented empirical findings that highlight the significance of sustainable logistics in reducing environmental uncertainty and improving organizational performance. Furthermore, the significance of green human resource management (GHRM) in enhancing organizational adaptability is underscored by Onyango [153] and Nurimansjah [154]. Collectively, these studies provide evidence that implementing green logistics management practices plays a crucial role in bolstering the resilience of supply chains, thereby empowering organizations to navigate environmental challenges adeptly.

The study conducted by Teece et al. [46] found that green logistics management practices play a crucial role in connecting green innovation strategies with supply chain resilience. The dynamic capabilities theory supports this perspective. These practices facilitate organizations' effective navigation of environmental challenges, thereby enhancing their supply chains' adaptability and robustness. According to the study conducted by Li et al. [30], the implementation of green supply chain management (GSCM) practices has been shown to improve manufacturing performance and stimulate green innovation, ultimately strengthening resilience. Karim et al. [155] and Khan et al. [156], respectively, have demonstrated the crucial role of green supply chain management (GSCM) in advancing the environmental performance of organizations and mediating the impact of Industry 4.0 technologies on operational and innovation performances. Jan et al. [157] underscore the strategic significance of green supply chain management (GSCM) in fostering sustainability and resilience within manufacturing supply chains. These studies collectively confirm the crucial role of green logistics in mediating the relationship between green innovation strategies and improved supply chain resilience. They show how green innovation, made possible by green logistics techniques, greatly improves resilience. This corpus of evidence enhances the scholarly conversation surrounding the strategic amalgamation of green innovation and logistics to enhance the resilience of supply chains.

The relationship between the green innovation strategy and green logistics management practices is notably strengthened in less structurally complex supply chains, aligning with Pant et al. [111], who highlight the importance of managing structural SC complexity for better innovation deployment. De Stefano and Montes-Sancho [115] further affirm that reducing complexity aids in managing GHG emissions more efficiently, advocating for simpler supply chain structures to enhance green logistics practices. Aitken et al. [113]

suggest that simplifying supply chains can significantly improve the implementation and effectiveness of green practices. However, Bode and Wagner [112] point out the challenges upstream complexity poses, including increased supply chain disruptions. Olivares Aguila and El Maraghy [158] argue that streamlined networks better support green innovations, while Memiş [119], Hussain et al. [26], and Iftikhar et al. [120] emphasize that strategic complexity management, through technological or structural adjustments, is crucial for enhancing green logistics and innovation strategies. These insights collectively assert that managing or reducing structural complexity is a strategic necessity, crucial for amplifying the impact of green innovation and logistics management practices.

Dynamic supply chain (SC) complexity was found to moderate the relationship between green logistics management practices and supply chain resilience, with a stronger relationship in less dynamically complex supply chains. Chen et al. [159] observed that downstream complexity impacts resilience negatively, underscoring the importance of managing dynamic complexity. Hussain et al. [26] and Zhang et al. [36] further emphasize that reducing dynamic complexity aids in enhancing resilience and green innovation performance, especially through supply chain agility. Iftikhar et al. [119] introduce the role of big data analytics in addressing dynamic complexity's effects on resilience, suggesting technological solutions as effective for managing dynamic complexity and boosting resilience. These results show that dynamic complexity has a big effect on how well green logistics practices work to make supply chains more resilient. This supports the need for strategic and technological approaches to reduce dynamic complexity for better resilience outcomes.

6. Conclusions

6.1. Theoretical Contribution

This research innovates by synthesizing the resource-based view (RBV), dynamic capabilities theory, and contingency theory to dissect the intricate relationship between supply chain management and sustainability, addressing notable gaps in the current literature.

Our research demonstrates how green innovation strategies, based on the resource-based view (RBV) framework, significantly enhance the resilience of supply chains. The resource-based view (RBV) theory posits that organizational resources play a crucial role in achieving a competitive advantage, a concept that also applies to the practice of green supply chain management. This study supports the empirical findings of de Sousa Jabbour et al. [160] and Tseng et al. [63], which demonstrate the importance of green innovation in promoting environmental sustainability and improving supply chain resilience by facilitating adaptation to ecological changes. In addition, our analysis demonstrates the beneficial effects of green innovation on green logistics management practices from the perspective of the resource-based view (RBV), establishing a strong foundation for the development of sustainable logistics practices. The effectiveness of firms implementing green innovation strategies in green logistics practices, resulting in improved environmental and operational outcomes, is substantiated by the confirmatory research conducted by Wiengarten et al. [82] and Zhu et al. [161]. The results of our study support and expand upon the existing theoretical framework by clarifying the significant impact of green innovation on logistics management. This study makes a valuable and original theoretical contribution to the field.

The significance of green logistics practices, such as environmentally friendly transportation and sustainable warehousing, in strengthening supply chain resilience is emphasized by empirical evidence from studies conducted by Sheu et al. [162] and Dubey et al. [163]. Implementing these practices is crucial for reducing vulnerabilities and strengthening the ability to recover after disruptions. This represents a significant step forward in building resilient supply chains through sustainability. In addition, our study expands the resource-based view (RBV) framework by highlighting the importance of Business Data Analytics Capability (BDAC) as a crucial strategic resource in the context of green supply chain management. The findings from Li et al. [30] and Govindan et al. [164] are crucial in illustrating the role of BDAC in fostering the development of environmentally sustainable operational abilities and improving the flexibility of supply chains. This results in a long-lasting advantage in competition, highlighting the crucial role of technological innovation in promoting environmental enhancements in supply chains.

Our research examines how green logistics management practices help connect green innovation strategies to improved supply chain resilience. We base our findings on empirical evidence from recent studies conducted by Al-Khatib [165] and Shahzad et al. [166]. These studies illustrate how organizations adjust and rearrange themselves in reaction to environmental challenges by implementing green logistics strategies. This showcases the practical implementation of the dynamic capabilities theory in promoting supply chain resilience in the face of ecological concerns. Pranee et al. [152] expand on this theoretical analysis by emphasizing the crucial significance of strategic planning, environmental sustainability, innovation, and learning in the operational achievements of community enterprises. This research supports the dynamic capabilities theory by demonstrating how ongoing innovation and learning processes enable organizations to successfully address environmental challenges, thereby improving green supply chain management. Teoh et al.'s [167] research contributes to this discourse by examining the relationship between environmentally sustainable supply chain practices and the operational efficiency of small and medium-sized enterprises (SMEs). The results highlight the beneficial effects of eco-design, packaging, and reverse logistics on operational efficiency and performance. This supports the viewpoint of the dynamic capabilities theory that adaptable and responsive supply chain practices are crucial for attaining environmental sustainability objectives.

Our research investigates the impact of supply chain complexity on the effectiveness of green innovation strategies and logistics management practices. Utilizing the research of Kotb Kholaif et al. [168] and Xue and Wang [29], we investigate the intricate impacts of institutional pressures and technological capabilities on initiatives related to managing green supply chains. This study supports the idea from the contingent theory that no one strategy works for everyone. It also shows how external factors can have a big effect on how well green supply chain initiatives work. Furthermore, Tang's [169] research significantly contributes to our theoretical framework by highlighting the critical role of digital transformation in enhancing collaboration and reducing carbon emissions within green supply chains. This text discusses how digital technologies help in managing intricate structural difficulties in supply chains, supporting our claim that technological progress is crucial in overcoming challenges caused by supply chain complexity. This facilitates the implementation of more efficient strategies for green innovation.

Okogwu et al. [147] conducted a crucial study that illustrates the complex difficulties involved in incorporating sustainable materials into supply chains. It emphasizes the substantial influence of structural and dynamic complexities on the implementation and efficacy of green logistics management practices. This is consistent with ongoing discussions about the intricacies of sustainable supply chain management, but it goes further by specifically emphasizing the various challenges involved in actually putting it into practice. Shaharudin and Fernando [170] conducted a study that delves into the intricate nature of cold supply chains for perishable products, highlighting the critical role of technological and logistical advancements in enhancing resilience and sustainability. This study enhances the overall discussion by offering specific insights on how organizations can effectively manage the challenges of cold supply chains through innovative strategies. As a result, it deepens our understanding of resilience in highly specialized supply chain contexts. Baah et al. [171] conducted a study that scrutinizes the effects of government policies and subsidies on logistics and supply chain innovations. The research highlights the substantial influence of external incentives and the intricate dynamics of environmental sustainability practices. This study highlights the significance of regulatory assistance in promoting innovative and environmentally friendly supply chain strategies, providing a detailed perspective on how policy frameworks can propel sustainable supply chain management.

Our study improves theoretical understanding by combining ideas from three different theoretical frameworks: green innovation, logistics management, and supply chain resilience; these ideas are then combined with real-world evidence to make a complete model. This model clarifies the circumstances in which green innovation strategies and practices produce the best results in improving supply chain resilience. It fills a gap in the existing literature by providing specific details on the conditions that enhance these advantages. Our work combines theoretical frameworks with empirical validation to offer a detailed perspective on how to strategically integrate sustainability into supply chain management. This study addresses a significant gap in the current research by providing empirical evidence to support the proposed integrated theoretical model. As a result, it contributes to discussions in the fields of supply chain management, sustainability, and organizational theory.

Our main contribution is to clearly explain the significant influence of technological resources and capabilities, the crucial role of green logistics practices as a mediating factor, and the limited effectiveness of strategies aimed at strengthening supply chain resilience. This thorough analysis sets a definitive direction for future investigation in the field of green supply chain management. Furthermore, it provides valuable guidance for professionals navigating the complex dynamics of sustainability in supply chains, making it a valuable contribution to both the academic and practical knowledge of sustainable supply chain resilience.

6.2. Practical Implications

The practical implications of this research are significant for manufacturing firms in Turkey, as well as for practitioners and policymakers in the broader context of supply chain management and sustainability. The recommendations provided are carefully formulated to closely align with the supported hypotheses, to improve the research's practicality and influence in real-life contexts.

Embracing green innovation strategies is not only a means for firms operating in the Turkish manufacturing sector to engage in environmental stewardship but also a strategic decision to enhance supply chain resilience and optimize green logistics management practices. It is highly recommended that companies capitalize on Turkey's expanding digital infrastructure and government incentives to promote sustainable practices that incorporate environmentally friendly technologies and processes. This approach should be given particular emphasis in supply chains that are less structurally complex, as the implementation of green strategies can be more direct and influential.

Manufacturers ought to allocate resources for the adoption of big data analytics and other digital tools to augment their green dynamic capabilities and fortify the resilience of their supply chains. This entails implementing IoT technology to monitor logistics operations in real time and utilizing blockchain technology to improve transparency and traceability in environmentally friendly logistics practices. These technologies contribute to achieving environmental objectives and confer competitive advantages in the context of the growing digital landscape of global markets.

To proficiently execute green innovation strategies, organizations should prioritize the establishment of collaborative alliances with technology providers and active engagement in industry consortia that advocate for sustainability standards. By actively involving stakeholders such as customers, suppliers, and regulatory bodies, it is possible to ascertain the key focus areas for green innovation and logistics practices. This approach guarantees that initiatives align with market demands and regulatory obligations.

Embracing a culture that emphasizes ongoing enhancement and flexibility is essential for effectively managing the ever-changing complexities of supply chains. It is recommended that organizations implement strategies to engage in continuous environmental scanning and learning. These strategies include organizing sustainability-focused workshops, fostering collaborations across different industries, and actively participating in global sustainability networks. This will allow them to proactively anticipate and adapt to emerging trends and regulatory changes, thereby ensuring their environmentally friendly practices' continued effectiveness and relevance.

Facilitating the transition to greener supply chains is heavily reliant on the active involvement of policymakers. Suggestions include formulating policies that establish explicit incentives for green innovation, such as implementing tax exemptions for investments in sustainable technologies, the provision of grants for research about green logistics practices, and establishing recognition initiatives for companies that demonstrate leadership in sustainability. These policies can potentially reduce the challenges to implementing environmentally friendly practices and promote extensive involvement from the industry.

Incorporating green innovation and logistics management practices gives companies a chance to augment their corporate social responsibility (CSR) profiles and make valuable contributions towards wider sustainability objectives. Companies must effectively convey their environmentally conscious endeavours through sustainability reports and marketing campaigns, thereby emphasizing their dedication to ecological guardianship and societal accountability. This aligns with environmental goals, enhances brand image, and fosters customer loyalty.

Firms should strive to measure the advantages of implementing environmentally friendly practices, such as decreasing energy usage, waste generation, and greenhouse gas emissions, while also achieving cost savings through improved efficiency. Illustrating the concrete advantages of these initiatives can aid in constructing the rationale for sustainability and thereby promote additional investment in environmentally friendly practices.

6.3. Future Studies and Limitations

Future research should broaden the geographic and sectoral scope to enhance generalizability and employ longitudinal designs to elucidate causal relationships. Emphasizing advanced statistical and machine learning techniques will address biases and improve objectivity, offering a nuanced understanding of the dynamics at play.

A focused exploration into the role of digital technologies, such as blockchain and AI, in green innovation strategies will provide actionable insights for enhancing supply chain resilience. This should be complemented by an investigation into the moderating effects of organizational culture and stakeholder pressure, utilizing mixed-methods research to capture the complex interplay between these factors and sustainable supply chain management.

By expanding the research framework and incorporating innovative methodologies, future studies can offer a more robust and comprehensive understanding of how green innovation strategies contribute to sustainable supply chain management, paving the way for practical applications and theoretical advancements in the field.

This study's limitations stem from its narrow geographic focus on Turkey, and its reliance on self-reported data from managers, which may introduce bias. Additionally, its cross-sectional design limits causal inferences between green innovation strategies and supply chain resilience. An important limitation of this study is its focus on a simplified representation of the supply chain, primarily concerning the focal enterprise manufacturers and their immediate input and output tiers. While this approach aligns with common practices in supply chain research, it might not fully capture the complexities and the dynamics of more extensive supply chain networks that include multiple tiers and diverse stakeholders. Future research could extend this work by incorporating a broader spectrum of supply chain participants, including secondary suppliers and end customers, to provide a more comprehensive view of the network's dynamics and interactions. This would enhance the understanding of how green innovation and logistics management practices impact the entire supply chain ecosystem. It is important to acknowledge that the survey questions, which primarily targeted focal enterprises along with their immediate suppliers and buyers, are structured to reflect the dynamics and interactions within one tier of the supply chain. Consequently, the findings may predominantly capture these limited interactions. This scope limitation restricts the generalizability of our results to more complex supply chain structures involving multiple tiers. Future studies could expand upon our research by designing survey instruments that capture interactions across multiple tiers of the supply chain, thereby offering a deeper and more nuanced understanding of supply chain dynamics.

Author Contributions: Writing—original draft, A.I.; Supervision, A.K., A.A. and A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted in accordance with the ethical standards of the University of Mediterranean Karpasia Institutional Review Board (IRB), confirming adherence to ethical guidelines and protocols for research involving human subjects.

Informed Consent Statement: Written informed consent was acquired from all participants prior to their involvement in the research.

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author, Ahmad Alzubi, upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Measurement items.

Green Innovation Strategy (Chan, 2005) [127]	
1.	To what extent has your firm modified its business practices or operations to reduce impact on animal species and natural habitats?
2.	To what extent has your firm undertaken voluntary actions (i.e., actions that are not required by regulations) for environmental restoration?
3.	To what extent has your firm modified its business practices to reduce wastes and emissions from operations?
4	To what extent has your firm modified its business practices or operations (e.g., through recycling) to reduce purchases of non-renewable materials, chemicals, and components?
5.	To what extent has your firm reduced the use of traditional fuels by the substitution of some less polluted energy sources?
6.	To what extent has your firm modified its business practices or operations to reduce energy consumption?
7.	To what extent has your firm modified its business practices or operations to reduce the environmental impacts of its products?
Green logistic management practices (Baah et. al., 2020 [129]; Longoni et. al., 2018 [130]; Zaid et. al., 2018) [131]	
1.	Engage in reverse logistics practices.
2.	Development of green reward schemes and compensation.
3.	Engage in employee and stakeholder green training, and monitoring and evaluating of environmental policies and practices.
4.	Use of sustainable transportation, product packaging, and distribution.
Structural SC complexity (Bozarth et. al., 2009 [132]; Bode and Wagner, 2015 [113])	
1.	Our firm serves a large number of customer bases.
2.	Our firm has a large number of first-tier suppliers.
3.	All of our customers desire essentially the same products ®.
Dynamic SC complexity (Bozarth et al. 2009 [132]; Brandon-Jones et al. 2014 [70])	
1.	We seek short lead times in the design of our supply chains.
2.	Our company strives to shorten supplier lead time, to avoid inventory and stockout.
3.	We can depend upon on timely delivery from our suppliers.

Table A1. *Cont.*

Supply Chain Resilience (Golgeci and Ponomarov 2015 [133]; Brusset and Teller, 2017 [134])	
1.	Our firm is able to adequately respond to unexpected disruptions by quickly restoring its product flow.
2.	Our firm is well-prepared to deal with financial outcomes of potential supply chain disruptions.
3.	Our firm has the ability to maintain a desired level of control over structure and function at the time of disruption.
4.	We deploy alternative plans associated with identified risks.

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