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Decarbonization through supply chain innovation: Role of supply chain collaboration and mapping

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ABSTRACT

The urgency of reducing carbon emissions has intensified amid escalating climate change concerns. Supply chain innovation practices are increasingly recognized as critical enablers of decarbonization by fostering efficiency, sustainability, and carbon reduction strategies. Against this backdrop, this study examines the role of SCIP in supply chain decarbonization. We also explore how supply chain collaboration and supply chain mapping can play a role in mediating the impact of SCIP, if any, on decarbonization. The study is contextualized in Electrical and Electronics sector of Malaysia. Data were collected through close-ended questionnaire from 156 firms. We employed Partial Least Squares Structural Equation Modeling to analyze these relationships. The results confirm a significant direct impact of SCIP on SCD, underscoring the pivotal role of innovation in sustainability efforts. However, contrary to conventional wisdom, SCC does not significantly mediate this relationship, suggesting that collaboration alone may not directly enhance decarbonization outcomes. In contrast, SC mapping plays a crucial mediating role, highlighting its importance in translating SCIP into effective carbon reduction strategies. These findings provide theoretical contributions to supply chain sustainability literature by distinguishing between collaboration and mapping as enablers of decarbonization. Practically, the study underscores the need for firms to invest in digital supply chain mapping tools to enhance visibility and strategic decision-making for decarbonization. Future research should explore industry-specific variations and the role of emerging digital technologies in strengthening supply chain sustainability.

1. Introduction

Decarbonization has evolved into an urgent global priority, compelling industries to embrace innovative strategies that minimize environmental harm. Heightened regulatory demands, growing consumer awareness, and broad sustainability imperatives have intensified the need to reduce carbon emissions and adopt greener business practices. In this context, supply chain innovation has emerged as a pivotal element in decarbonization efforts, helping firms reconfigure their operations to address both ecological and competitive demands. The progression of carbon trading frameworks and increasingly stringent environmental regulations has accelerated this transition, driving companies to embed sustainability-driven, innovative approaches into their supply chains (Mubarik et al., 2021). Specifically, Supply Chain Innovation Practices, *encompassing the implementation of green technologies, sustainable procurement, and process optimization*, offer measurable pathways to lower greenhouse gas (GHG) emissions and reduce waste, thereby contributing to the realization of sustainability objectives (Kusi-Sarpong et al., 2024). Beyond environmental benefits, organizations that incorporate sustainability into their supply chains often realize improved competitive positioning, risk mitigation, and enhanced stakeholder trust (Reza et al., 2024).

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While these individual innovation measures are crucial, Supply Chain Collaboration stands to amplify their impact by fostering shared knowledge, pooling resources, and cultivating joint sustainability initiatives among supply chain partners (Sudusinghe and Seuring, 2022). Collaborative alliances can drive decarbonization by facilitating open communication, co-creating innovative solutions, and improving operational synergies (Duong and Chong, 2020). Although both SCIP and SCC are acknowledged as central to environmental sustainability, how they jointly shape supply chain decarbonization (SCD) remains insufficiently explored. Existing scholarship underscores the importance of sustainable supply chains but seldom distinguishes the specific contributions of innovation-oriented practices from more generalized operational improvements (Mubarik et al., 2021). Moreover, the literature on SCC is not unanimous: while some studies depict its beneficial influence, others highlight alignment complexities and inefficiencies. These mixed findings underscore the need for a refined investigation into whether—and how—SCIP and SCC combine to further carbon reduction goals.

We situate our research in the Malaysian Electrical and Electronics sector. Data from 156 Malaysian E&E firms were collected using a close-ended questionnaire, and Partial Least Squares Structural Equation Modeling was applied for empirical analysis. In doing so, our work extends existing literature in two key ways. First, it explicates the unique interplay of innovation and collaboration and clarifies why focusing on their combined effects is necessary to appreciate their full potential in lowering carbon footprints. Second, it highlights the importance of sector-specific dynamics: though general insights into sustainable supply chains exist, our sector-centric analysis sheds light on challenges and opportunities unique to E&E supply chains in emerging economies, advancing the theoretical discourse on industry-contextual sustainability.

The remainder of the paper is organized as follows. The subsequent section synthesizes extant research, building a theoretical foundation for our hypotheses. We then detail our methods, including the data collection strategy and analytical approach. This is followed by the results section, where we present key findings and interpret them in light of current scholarship and industry practices. The paper concludes by discussing theoretical implications, offering managerial recommendations, and identifying avenues for further inquiry.

2. Literature review

In this section, we comprehensively discuss the definitions, and dimensions, of the key variables of the study, providing a clear understanding of how they are conceptualized and applied in this study. Section 2.1 discusses *Supply Chain Innovation Practices*, detailing what constitutes innovation within the supply chain, its various dimensions, and its significance in driving efficiency and competitiveness. Similarly, the subsequent subsections provide a thorough exploration of Supply Chain Decarbonization, Supply Chain Collaboration, and Supply Chain Mapping.

2.1. Supply chain innovation practices

Supply chain innovation practices are considered as a significant way to exploiting process and technology innovations to finding novel ways for managing supply chains. The concept of SCIP has evolved significantly over time, beginning with its origins in the early efforts to streamline logistics and manufacturing processes. Initially, the focus was on optimizing individual elements of the supply chain, such as inventory management and transportation logistics, aiming for efficiency and cost reduction (Fine, 1998). This foundational perspective underscored the importance of continuous improvement in the operational aspects of the SC but did not fully encapsulate the broader strategic implications. The earlier definition of SCIP emphasized the integration of information technology to enhance visibility and coordination across the supply chain (Flint et al., 2008; Arlbjørn et al., 2011). This definition highlighted the role of digital technologies in facilitating real-time data exchange and collaboration among supply chain partners. However, it somewhat overlooked the importance of innovation in product development and the integration of customer insights into the supply chain process (Arlbjørn et al., 2011; Malacina & Teplov, 2022; Shafique et al., 2024; Veile et al., 2024).

Initially, SCIP emerged as a response to the need for streamlining logistics and manufacturing through the digitization enabled by Industry 4.0. In this phase, digital technologies—such as the IoT, big data analytics, and cloud computing—were harnessed to improve supply chain visibility, coordination, and real-time decision-making. This digital transformation provided the tools for advanced supply chain mapping, predictive analytics, and enhanced information exchange among partners. Building on the strong digital foundation laid by Industry 4.0, Industry 5.0 represents an evolutionary step that reintroduces a human-centric perspective into supply chain management. Whereas Industry 4.0 focused predominantly on technological advancements and automation, Industry 5.0 emphasizes the integration of human creativity, critical thinking, and collaborative ecosystems. Building on this, studies focused the concept of end-to-end supply chain optimization, incorporating the notion of aligning supply chain strategies with business objectives. This approach broadened the scope of SCIP to include not just technological innovations, but also strategic initiatives aimed at creating value for customers and achieving competitive advantage (Afraz et al., 2021; Mubarik et al., 2021). Despite this broader perspective, this definition still lacked emphasis on sustainability and the social dimensions of supply chain innovation. Addressing these gaps, studies like Gupta et al. (2020) the SCIP incorporated the principles of sustainability and social responsibility, recognizing that innovation in supply chains also entails developing practices that are environmentally sustainable and ethically sound. This definition acknowledged the increasing importance of green supply chain practices and corporate social responsibility in driving innovation. However, it did not fully explore the potential of leveraging advanced analytics and big data for predictive insights and decision-making in the supply chain. Recent studies have highlighted the role of advanced analytics, big data, and artificial intelligence in enhancing supply chain agility and responsiveness. This perspective underscored the importance of data-driven decision-making and the utilization of AI to anticipate market changes, optimize supply chain performance, and personalize customer experiences. While this definition embraced the technological advancements in SCI practices, it could have further emphasized the human and organizational aspects of fostering a culture of innovation.

In the context of Industry 5.0, the concept of collaborative ecosystems is in limelight, focusing on the human and organizational dimensions of innovation. It stressed the importance of creating a culture that supports innovation, collaboration, and continuous learning among all stakeholders involved in the supply chain. This approach recognized that technology alone is not sufficient to drive innovation; organizational culture, leadership, and the development of skills and capabilities are equally crucial. Majority of the recent studies (Lai et al., 2023; Zheng et al., 2024; Yan et al., 2024) defined SCIP as a comprehensive approach that encompasses the adoption of digital technologies, strategic alignment, sustainability, advanced analytics, collaborative ecosystems, and adaptability to external forces. This definition acknowledges that supply chain innovation is a multifaceted process that involves not only technological and operational improvements but also strategic, social, and environmental considerations.

Drawing upon the above discussion, the present study defines SCIP as dynamic, integrated practices that leverage digital technologies, strategic alignment, sustainability principles, and advanced analytics to enhance the efficiency, agility, and responsiveness of the supply chain. These practices are grounded in a culture of collaboration and continuous learning, extend beyond organizational boundaries to include partners and stakeholders, and are responsive to external market dynamics and regulatory environments.

2.2. Supply chain decarbonization

Decarbonization has evolved from a embryonic concept into a global imperative, initially focused on reducing carbon emissions from direct, energy-intensive activities. This evolution reflects a growing awareness of impacts of climate change and a recognition of the urgent need to transition towards low-carbon economies. Initially, decarbonization efforts concentrated on enhancing energy efficiency and transitioning to renewable energy sources in sectors like power generation and transportation (Spiller, 2021). As the understanding of carbon footprints deepened, the scope of decarbonization expanded to include indirect emissions, leading to comprehensive strategies encompassing all sectors of the economy (Zhang et al., 2022). It also brought *supply chain decarbonization* under limelight. It emerged as a critical area within this broader decarbonization movement, recognizing that significant emissions are not just the result of direct operations but also embedded within the global supply chains. This recognition led to diverse definitions and approaches towards SCD, reflecting its complexity and the varied nature of supply chains across industries. It emphasizes the reduction of direct emissions within the logistics and transportation aspects of the supply chain. This perspective focuses on optimizing routes, increasing fuel efficiency, and transitioning to lower-carbon transportation modes (Brinken, J., Pabsch, C., & Behrendt, 2022). However, it tends to overlook the broader scope of supply chain activities and their embedded emissions.

Moving beyond logistics, scholars broaden the scope to include the sourcing of raw materials and the manufacturing processes. It advocates for the selection of suppliers and materials that have lower carbon footprints and the adoption of cleaner manufacturing technologies. While this definition expands the focus, it sometimes underemphasizes the end-of-life stage of products and the potential for emissions reductions through recycling and circular economy practices. This the reasons few of the recent scholars like Khan et al. (2022) has introduced the concept of the circular economy into SCD, highlighting the importance of designing out waste and maximizing the reuse and recyclability of materials. This approach underlines the role of supply chain design in minimizing carbon emissions, not just through direct reductions but also by fundamentally rethinking how products are made and used (Spiller, 2021; Zhang et al., 2022).

Highlighting the need and significance of digitalization, Mubarik et al. (2021) integrates the digital technologies in achieving Supply Chain Decarbonization. They argue that AI and blockchain can play a major role in SCD by enhancing transparency, tracking emissions across the supply chain, and identifying hotspots for intervention. They further argue that SCD needs to be taken as a holistic effort that encompasses direct and indirect emissions reductions, embraces circular economy principles, leverages technological innovation, and fosters collaboration across all supply chain stakeholders (Mubarik et al., 2021). It recognizes that achieving significant decarbonization requires actions at every stage of the supply chain—*from raw material extraction through to product design, manufacturing, distribution, use, and end-of-life management*.

Drawing upon the above, we argue that there is a need to differentiate between supply chain decarbonization efforts and actual supply chain decarbonization. SCD efforts is multi-facet approach aiming to drastically reducing greenhouse gas emissions across the entire supply chain. It involves direct actions to lower emissions from transportation and logistics, the adoption of sustainable sourcing and manufacturing practices, and the integration of circular economy principles to minimize waste and maximize resource efficiency. Furthermore, it takes a holistic approach and leverages DTs to enhance transparency, enable precise tracking of emissions, and facilitate data-driven decision-making. Whereas, realized or actual SCD refers to the tangible and measurable reduction in greenhouse gas (GHG) emissions across the entirety of supply chain operations of a firm. This encompasses direct actions leading to reduced carbon outputs, such as adopting renewable energy sources, enhancing energy efficiency, and transitioning to low-carbon transportation and logistics options. It also includes the implementation of CE practices aimed at reducing waste and extending the lifecycle of resources, thereby contributing to emissions reduction. Decarbonization further involves engaging with suppliers and partners to ensure that they too are making verifiable progress in reducing their carbon footprint. This process is not solely about mitigating direct emissions but also about investing in carbon offsetting projects to compensate for unavoidable emissions, thus moving towards the organization's comprehensive long-term decarbonization targets. Actual SCD is evidenced by a decrease in the carbon footprint per unit of product shipped, improved supply chain resilience against carbon-related risks, and a clear trajectory towards meeting or exceeding regulatory and societal expectations for environmental sustainability.

We focus on the actual or realized SCD and operationalize it accordingly in the methodology section of the study.

2.3. Supply chain collaboration

Supply Chain Collaboration has increasingly become a focal point of interest in recent studies, reflecting its critical role in enhancing the efficiency, resilience, and competitiveness of supply chains (Duong and Chong, 2020; Sudusinghe & Seuring, 2022). Amidst growing complexities in global markets, technological advancements, and heightened expectations for sustainability, the dynamics of supply chain collaboration have evolved, highlighting various dimensions and facets that contribute to its understanding and implementation. At its core, SCC is predicated on the notion of firms working together across the SC to achieve mutual benefits that are unattainable when operating independently. This collaboration spans *from raw material suppliers to end-product retailers,* encompassing all the entities involved in the flow of goods, services, information, and finances. Recent studies (e.g., Kusi-Sarpong et al., 2022) have emphasized the importance of transparency, trust, and shared goals as foundational elements of successful collaboration. Transparency allows for the free flow of information, reducing uncertainties and enabling better coordination. Trust, on the other hand, facilitates long-term partnerships and encourages the sharing of risks and rewards. Lastly, having shared goals ensures that all parties are aligned towards common objectives, optimizing the entire supply chain rather than individual components.

The dimensions of SCC include operational, strategic, and technological collaboration. Operational collaboration involves joint activities such as shared logistics, synchronized production planning, and inventory management, aimed at improving day-to-day efficiency and responsiveness. Strategic collaboration, however, goes deeper, involving long-term investments, joint product development, and market expansion strategies that are mutually beneficial. Technological collaboration has gained prominence with the advent of DTs, emphasizing the integration of information systems, the use of blockchain for transparency, and the application of artificial intelligence for predictive analytics (Attaran, 2020). These dimensions are not mutually exclusive but are interrelated, contributing to a holistic approach to supply chain management. Recent studies have also highlighted the facets of SCC in terms of its scope and intensity. The scope of collaboration can range from dyadic relationships, involving two firms, to network collaborations that encompass multiple entities across the supply chain. The intensity of collaboration can vary from low-level information sharing to deep, strategic partnerships that may even involve co-creating value (Kusi-sarpong, Mubarik et al., 2021). The evolution of SCC is marked by a shift from competitive to cooperative paradigms, where the focus is on building a competitive advantage for the entire supply chain rather than individual firms. This shift is driven by the recognition that challenges such as demand fluctuations, supply disruptions, and sustainability goals require a collaborative approach to address effectively.

Furthermore, the role of DTs in facilitating SCC has been a significant focus of recent research. Technologies such as IoT, AI, and cloud computing have transformed the capabilities for real-time data sharing and collaboration, enabling more agile and responsive supply chains. These technologies also support the sustainability aspect of SCC by providing tools for monitoring and reducing carbon footprints, ensuring ethical sourcing, and promoting circular economy practices (Sudusinghe & Seuring, 2022; Reza et al., 2024).

In light of the above, SCC can be defined as a strategic alignment and operational synergy among all entities in a SC, facilitated by trust, transparency, and technology. It encompasses a multifaceted approach involving operational efficiencies, strategic initiatives, and technological integrations, aimed at achieving shared goals. For measuring SCC, Construct of supply chain collaboration have adopted and refined from Simatupang and Sridharan (2005), Sudusinghe and Seuring (2022), Andalib Ardakani et al. (2023), Al-Omoush et al. (2023), Javed et al. (2024).

2.4. Supply chain mapping

Supply Chain Mapping (SCMap) has garnered significant attention in recent years as businesses seek greater transparency and resilience in their supply chains (Choi et al., 2020; Oliveira-Dias et al., 2022). This increased focus reflects the complex, global nature of modern supply chains and the need to mitigate risks and optimize performance across multiple tiers of suppliers, manufacturers, and distribution networks. Recent studies (Choi et al., 2020; Mubarik et al., 2021) have emphasized SCMap as a critical tool for achieving these objectives, highlighting its various dimensions and facets. At its essence, SCMap involves the detailed visualization and analysis of the flow of materials, information, and finances from the raw material stage through to the end consumer. This process not only identifies the key entities and activities within the supply chain but also examines the relationships and dependencies among them. One of the primary goals of SCM is to provide a comprehensive understanding of the supply chain's structure and dynamics, enabling firms to identify potential bottlenecks, vulnerabilities, and opportunities for improvement. Mubarik et al. (2021) contribute to the discourse by stressing the importance of a multi-tiered approach to SCMap. Their research highlights that visibility into first-tier suppliers is insufficient in the present interconnected supply chains. Instead, firms must seek to map out second-tier suppliers and beyond, potentially extending to raw material providers. This depth of mapping is crucial for several reasons, including risk management, sustainability practices, and compliance with international standards and regulations. Another dimension of SCM highlighted in recent literature is the role of digital technologies in facilitating mapping efforts (Khan et al., 2022). Technologies such as blockchain, IoT, and AI are increasingly being utilized to enhance the accuracy, efficiency, and real-time capabilities of supply chain maps. These technologies enable the automatic collection and analysis of data, providing firms with up-to-date information on their supply chain activities and facilitating rapid response to disruptions or changes in demand.

Sustainability and ethical sourcing have also emerged as important facets of SCMap (Mubarik et al., 2021). Firms are increasingly expected to ensure that their supply chains do not contribute to environmental degradation or violate labor rights. SC Mapping can help firms identify where in their SC there may be risks of such issues, allowing them to take corrective action. This aspect of SCM is particularly relevant considering growing consumer and regulatory pressure for companies to demonstrate corporate social responsibility.

In addition to risk management and sustainability, SCM plays a pivotal role in strategic decision-making. By providing a clear overview of the supply chain, mapping allows firms to identify opportunities for optimization, such as reducing lead times, consolidating suppliers, or redesigning products for easier manufacturing. Furthermore, SCM can facilitate collaboration by helping partners identify mutual dependencies and areas where joint initiatives could enhance efficiency or innovation. Mubarik et al. (2021) has divided mapping into three streams: *upstream, midstream and down stream*. Upstream mapping focuses on the early stages involving raw material sourcing, highlighting the importance of sustainability and ethical practices by providing insights into suppliers' operations and material origins. This phase is pivotal for identifying environmental, labor, and resource scarcity risks. Midstream mapping transitions to the manufacturing and processing stages, where insights into production efficiency, quality control, and capacity optimization are crucial for operational improvement. Downstream mapping covers the distribution, sale, and delivery of products, focusing on the efficiency of distribution networks and customer satisfaction. Together, these mappings offer a holistic view of the supply chain, enabling firms to identify risks, optimize operations, and improve customer experiences, ensuring the supply chain's resilience, efficiency, and sustainability.

Reflecting on these various dimensions, SC Mapping can be cohesively defined as a comprehensive process that visualizes and analyzes the end-to-end flow of materials, information, and finances within a supply chain. It involves identifying all relevant entities, from raw material suppliers to end consumers, and examining the relationships, dependencies, and flows between them.

3. Theoretical exposition

The study takes theoretical support from RBV (Wernerfelt, 1984), and Natural Resource Based View (NRBV) (Hart, 1995) to model the impact of SCIP on SCD. Both RBV and NRBV theories provide a robust framework for understanding how SCI practices contribute to supply chain decarbonization (Barney, 1991). According to the RBV, firms achieve competitive advantage by deploying valuable, rare, inimitable, and non-substitutable (VRIN) resources and capabilities. In the context of supply chain management, SCI practices such as the adoption of green technologies, process innovations aimed at reducing waste, and the implementation of sustainable sourcing methods can be viewed as unique resources that enhance environmental performance and sustainability. These innovative practices enable firms to reduce their carbon footprint through more efficient use of resources and by fostering a culture of sustainability within the supply chain. Consequently, SCI practices, as strategic resources, contribute to achieving supply chain decarbonization by minimizing environmental impact and promoting sustainable growth, aligning with the broader goals of corporate social responsibility and environmental stewardship. Likewise, NRBV posits that firms can achieve competitive advantages by leveraging unique, sustainable resources and capabilities. It provides theoretical support for modeling the impact of SCIP on SCD by emphasizing green processes, green technologies, and resource optimization. These practices, such as adopting renewable energy or circular supply chains, reduce carbon emissions while enhancing firm performance, aligning environmental sustainability with strategic goals and fostering long-term resilience in dynamic markets.

The role of Supply Chain Collaboration (SCC) is underscored by the principles of relational governance. As elucidated by Wadood et al. (2022) in the context of Transaction Cost Economics (TCE), in situations where the future is unpredictable, the relational view and sociological perspectives advocate for relational governance as a superior governance mechanism. This approach, characterized by trust and social norms, is deemed more effective in facilitating the exchange of knowledge pertaining to social sustainability. SCT (Social Capital Theory) provides direct support to this view (Carey et al., 2011). The SCT emphasizes the strategic value of relationships and networks in achieving competitive advantage (Nahapiet, J., & Ghoshal, S. 1998). It suggests that collaborative relationships between firms and their supply chain partners can lead to unique inter-organizational resources and routines that are critical for achieving shared goals. In the framework of SC decarbonization, SCC acts as a mediating mechanism that enhances the effectiveness of SCI practices. Through collaborative efforts, firms and their partners can share knowledge, resources, and capabilities, leading to the co-creation of innovative solutions for reducing carbon emissions across the supply chain. Collaboration facilitates the diffusion of best practices, the integration of green technologies, and the joint development of sustainable products and processes, amplifying the impact of SCI on decarbonization efforts. Furthermore, SCC strengthens the resilience of supply chains, enabling them to respond more effectively to environmental regulations, market demands for sustainability, and the challenges posed by climate change.

The role of SC mapping is supported by Systems Theory, which at its core, views an organization or supply chain as a complex set of interrelated parts that work together to achieve a common goal. It posits that changes or innovations in one part of the system inevitably affect other parts, highlighting the importance of holistic management and coordination to ensure overall system effectiveness and sustainability (Caddy, I. N., & Helou, 2007; Puche et al., 2016). Applying Systems Theory to the context of supply chain decarbonization, SCI practices can be seen as interventions or changes introduced into the supply chain system to enhance its environmental performance. These innovations may include the adoption of green technologies, sustainable sourcing practices, or process improvements aimed at reducing carbon emissions. However, the effectiveness of these practices in achieving decarbonization goals is significantly influenced by how well they are integrated and coordinated across the entire supply chain. This is where SC Mapping plays a critical, mediating role. SCMap provides a comprehensive overview of the supply chain, identifying all actors, activities, and interactions involved in the creation and delivery of products. By mapping out these elements, organizations can gain insights into where and how SCI practices can be most effectively implemented to reduce carbon emissions. Furthermore, SCMap enables the identification of key leverage points within the supply chain where innovations can have the greatest impact on decarbonization. This systematic understanding facilitates the strategic allocation of resources and efforts, ensuring that SCI practices are not implemented in isolation but are instead integrated into the broader supply chain system for maximum effect. Moreover, ST underscores the interdependence of supply chain entities and processes. Through SCM, organizations can better understand these interdependencies and how SCI practices introduced at one stage of the supply chain can influence environmental outcomes at another. For instance, innovations in product design or packaging not only affect manufacturing processes but also have downstream implications for transportation efficiency and waste management. SCMap, by providing visibility into these connections, enables organizations to anticipate and manage the systemic effects of SCI practices, thereby enhancing their contribution to decarbonization. Further, SCMap facilitates the collaboration and coordination essential for effective systemic change. By making the structure and dynamics of the supply chain transparent, SCMap encourages communication and cooperation among supply chain partners. This collaborative environment is crucial for addressing the complex challenges of decarbonization, which often require concerted efforts across multiple supply chain stages and actors. Through joint planning, shared goals, and collective action, supply chain partners can leverage SCI practices more effectively to achieve significant reductions in carbon emissions.

4. Hypotheses development

This section reviews the relevant literature to develop the hypotheses of the study. Sub-section 4.1 discusses the relationship between Supply Chain Innovation Practices and Decarbonization. Sub-section 4.2 examines the role of Supply Chain Collaboration in the context of Supply Chain Innovation Practices and Decarbonization. Finally, Sub-section 4.3 discusses the impact of Supply Chain Mapping on Supply Chain Innovation Practices and Decarbonization.

4.1. SC innovation practices and decarbonization

The role of SCIP in facilitating SC decarbonization has garnered significant attention. Numerous studies (Spiller, 2021; Brinken, J., Pabsch, C., & Behrendt, 2022) and reports underscore the positive impact that SC practices (including SCIP) exert on the decarbonization of supply chains. For instance, World Economic Forum have highlighted how innovations in supply chain management, ranging from advanced analytics and blockchain for enhanced traceability to green logistics and sustainable sourcing, can significantly reduce carbon footprints. These innovations not only improve operational efficiencies but also lead to the adoption of cleaner, more sustainable practices across the supply chain, thereby contributing to overall carbon reduction. However, this narrative is not without its counterarguments. Some scholars argue that the relationship between SC innovation practices and supply chain decarbonization is not as straightforward as it appears (Gao et al., 2017; Gupta et al., 2020). Critics point out that the implementation of SC innovations can be capital-intensive and may not yield immediate environmental benefits. For example, the adoption of green technologies or the transition to renewable energy sources requires substantial initial investments and a long-term perspective, which may not be feasible for all firms. Additionally, there is a perspective that suggests the gains in efficiency afforded by SC innovations might lead to an increase in production and consumption—a phenomenon known as the *rebound effect*, which could potentially offset the environmental benefits of decarbonization efforts.

Despite these divergent views, the prevailing evidence and the urgent global need for decarbonization compel us to explore the relationship between SC innovation practices and supply chain decarbonization further. The contradictions in existing literature highlight the complexity of this relationship and underscore the necessity of a nuanced approach that considers various factors such as industry type, geographic location, and the specific nature of SC innovations. This leads us to posit the following hypothesis:

Hypothesis 1. SC Innovation practices improve SC decarbonization of a firm

4.2. SC innovation practices and decarbonization: role of SC collaboration

As discussed earlier, among the strategies deployed to achieve this goal, SCIP have emerged as a crucial lever. These SCIPs, ranging from adopting green technologies to implementing process improvements for energy efficiency, hold the potential to significantly reduce greenhouse gas emissions across the supply chain (Singhry, 2015; Liao et al., 2017; Liao et al., 2021). However, the effectiveness of these innovations in driving SC decarbonization is often contingent upon the level of collaboration among supply chain partners, Supply chain collaboration. SCC involves the strategic alignment and integration of processes, information, and goals across multiple stakeholders, including suppliers, manufacturers, and distributors. This cooperative approach is posited to positively mediate the relationship between SC innovation practices and SC decarbonization. The rationale behind this mediation is twofold. First, collaboration facilitates the sharing of knowledge and resources, enabling the adoption of innovative practices that one party alone might not be able to implement due to cost, expertise, or technological limitations. Second, through collaborative efforts, supply chain entities can achieve greater operational synchrony, leading to optimized logistics and inventory management that further contribute to reducing carbon emissions (Liao et al., 2021; Wadood et al., 2022). For instance, shared transportation modes and routes can minimize the number of trips required, thereby lowering fuel consumption and emissions. Despite these arguments in favor of the mediating role of SC collaboration, there are viewpoints that challenge this relationship (Khan et al., 2022). There are few arguments that SC collaboration can introduce complexity and slow down decision-making processes, especially when the parties have differing environmental priorities or when the distribution of costs and benefits of decarbonization initiatives is uneven. This discord can hinder the effective implementation of SC innovation practices aimed at reducing carbon footprints. Additionally, concerns about sharing sensitive information and potential competitive disadvantage can limit the depth of collaboration, thereby constraining the potential environmental benefits.

Considering the above perspectives, it becomes imperative to reconcile the findings to draw meaningful insights. The conflicting arguments suggest that while collaboration has the potential to amplify the benefits of SC innovation practices in terms of decarbonization, the realization of these benefits is contingent upon several factors, including the alignment of environmental goals, equitable sharing of costs and benefits, and effective management of collaborative relationships.

Given this context, it is hypothesized:

Hypothesis 2. SC Collaboration mediates the relationship between SC Innovation practices and SC decarbonization of a firm

4.3. SC innovation practices and decarbonization: role of SC mapping

Supply chain mapping represents a critical analytical tool that provides a comprehensive overview of the entire supply chain, identifying all the actors involved, from raw material suppliers to end consumers, and illustrating the flow of materials, information, and finances. This visibility is instrumental in pinpointing inefficiencies, potential risks, and opportunities for innovation within the supply chain (Mubarik et al., 2021). In the context of environmental sustainability, particularly supply chain (SC) decarbonization, the role of SC mapping emerges as a pivotal factor that could mediate the relationship between SC innovation practices and SC decarbonization efforts (Kusi-Sarpong et al., 2022).

The argument in favor of SC mapping as a positive mediator rests on its ability to enhance the effectiveness of SC innovation practices aimed at decarbonization. By providing a clear and detailed view of the supply chain, SC mapping allows firms to identify specific segments or processes that are major contributors to their carbon footprint. With this insight, organizations can target their innovation practices more effectively, whether through the adoption of green technologies, process optimizations, or modifications in the supply chain structure, such as shortening the supply chain or switching to suppliers with lower carbon footprints. Additionally, SC mapping facilitates the tracking of progress towards decarbonization goals by enabling the measurement of carbon emissions before and after the implementation of innovation practices. This not only aids in assessing the effectiveness of these practices but also helps in reporting and communicating sustainability achievements to stakeholders (Oliveira-Dias et al., 2022; Kusi-Sarpong et al., 2024).

Despite these potential benefits, some arguments challenge the mediating role of SC mapping in the association between SC innovation practices and SC decarbonization. Opponents argue that SC mapping, while valuable for visibility, does not automatically lead to the implementation of effective decarbonization strategies. The process of SC mapping can be resource-intensive, requiring significant time and financial investment, which might not always be feasible, especially for SMEs. Moreover, the mere identification of high-emission points within the supply chain does not guarantee that a firm has the capability or willingness to innovate in ways that effectively reduce those emissions. There can also be challenges related to data accuracy and availability, as well as the willingness of all supply chain partners to share sensitive information, which is crucial for creating an accurate and comprehensive map.

Reconciling these viewpoints, it becomes apparent that while SC mapping holds the potential to significantly mediate the relationship between SC innovation practices and decarbonization, its effectiveness is influenced by several factors, including the firm's commitment to sustainability, the availability of resources for mapping and subsequent innovations, and the cooperation of supply chain partners.

Therefore, we posit the third hypothesis:

Hypothesis 3. SC Mapping mediates the relationship between SC Innovation practices and SC decarbonization of a firm

The framework exhibited in Fig. 1, positions SCIP as a key driver directly influencing SC Decarbonization (H1), and also indirectly affecting it through SCC (H2a and H2b) and SC Mapping (H3a and H3b). The framework highlights SCC and SC Mapping as important mediating mechanisms that may amplify or clarify how innovative practices translate into decarbonization outcomes.

5. Method

The following two sections explore the context of this research: the first provides an overview of Electrical and Electronics Sector of Malaysia, outlining its significance, challenges, and current market dynamics. The second section describes our data collection and analysis approach, detailing the methodology used to ensure the accuracy and reliability of our findings and how these methods support the objectives of the study.

5.1. Population and sampling

The study focuses on electrical and electronics (E&E) sector of Malaysia. This sector holds a pivotal position in both the Malaysian and global economy, serving as a cornerstone for technological advancement, economic growth, and international trade. In Malaysia, this sector is the backbone of the industrial development and a major contributor to country's GDP, exports, and employment. Globally, the E&E sector is at the forefront of innovation, driving the development of new technologies and products that shape the future of various industries, from consumer electronics to renewable energy solutions. The export-oriented nature of E&E sector results in the development of a complex supply chain network that spans across borders, linking Malaysian businesses with global markets and supply chains. We selected this sector as focus of this study due to few key reasons. First, this sector has significant economic footprint and appears as a major energy consumer and carbon emitter. It underscores the urgency and potential to focus this sector. For the E&E sector, which is inherently innovation-driven, integrating SC innovation practices with sustainability objectives presents a strategic avenue to enhance competitive advantage while contributing to environmental goals. Second, the multi-layered, complex and intertwined SC characteristic of the E&E sector offer a rich context for exploring how innovation practices can facilitate decarbonization efforts.

5.2. Data collection and analysis

Data collection was conducted through a structured questionnaire, as detailed in Appendix-A. This questionnaire was derived from existing studies, tailored specifically to suit the context of this research. Notably, the construct of SC mapping was adapted from Mubarik et al. (2021) where the original construct comprised 25 items. To streamline the focus and relevance to our study, we condensed this to 15 items by excluding those deemed unrelated. Furthermore, item statements were carefully revised to ensure contextual alignment. Please see the questionnaire in the appendix.

Data were collected from 156 Malaysian E&E sector during the last quarter of 2023 and first quarter of 2024. Data were collected part of the larger project, aiming to investigate multi-dimensional aspect of E&E supply chain. Assistances of third-party organization was taken for data collection. All of the firms in the sectors were divided into three sizes: *small (36), medium (67) and large(53);* three demographics: *Penang(61), Selangor(43) and Kedah (52)* and four sectors: *consumer electronics(38),*

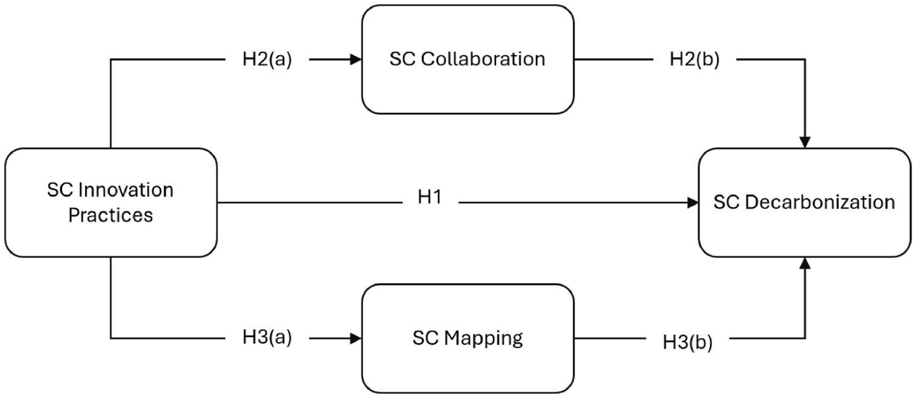

Fig. 1. Framework.

electronic components (47), industrial electronics (35), electrical products (36) (Malaysian Investment Development Authority-MIDA, 2024).

This study employs Partial Least Squares Structural Equation Modeling (PLS-SEM) for data analysis. PLS-SEM is particularly favored for its robustness in handling complex models and its ability to work efficiently with small to medium sample sizes, making it an ideal choice for exploratory research or studies aiming to build upon theoretical models. It is employed in two steps. The first step involves a Confirmatory Factor Analysis (CFA) of the constructs. This step assesses the reliability and validity of the constructs, confirming that each item reliably measures its respective construct and that the constructs are distinct from one another. It involves evaluating indicators such as Cronbach's alpha (CB alpha), composite reliability (CR), average variance extracted (AVE), and HTMT values, which together ensure that the measurement model is both reliable and valid. Following the successful validation of the constructs, the second step of the analysis engages in hypotheses testing through the structural model. This phase examines the strength and significance of the hypothesized relationships between constructs, utilizing path coefficients and statistical significance levels to draw conclusions about the proposed theoretical model.

6. Findings and discussions

6.1. Findings

The results of reliability and convergent validity for each construct are presented in Table 1 below. For Supply Chain Innovation Practices (SCIP), the factor loadings (FL) across items SCIP1 through SCIP12 range from 0.62 to 0.80, indicating a strong loading of items onto the construct, which suggests good indicator reliability. The Average Variance Extracted (AVE) for SCIP stands at 0.52, which exceeds the threshold of 0.5, affirming adequate convergent validity. The construct also demonstrates high reliability with a Composite Reliability (CR) of 0.916 and a Cronbach's Beta (CB) alpha of 0.74, both of which are above the commonly accepted thresholds of 0.7, indicating high internal consistency. For Supply Chain Decarbonization (SCD), the factor loadings range from 0.62 to 0.82, showcasing that each item reliably measures the construct. With an AVE of 0.5, SCD meets the criterion for convergent validity, and the reliability scores (CR = 0.9 and CB alpha = 0.77) suggest that the construct is consistently measured across its items.

Supply Chain Collaboration (SCC) exhibits factor loadings between 0.63 and 0.75, reflecting a strong relationship between items and the construct. The AVE is 0.5, indicating that the construct has good convergent validity. The CR and CB alpha values of 0.91 and 0.81, respectively, highlight the high reliability of SCC, showcasing the construct's internal consistency. Supply Chain Mapping (SCMap) features factor loadings from 0.62 to 0.82, suggesting that the items are good indicators of the construct. The AVE of 0.51 meets the minimum requirement for convergent validity. Reliability is also evidenced by a CR of 0.88 and a CB alpha of 0.73, indicating that SCMap is measured reliably across its various items.

The square root of AVE for each construct (SCIP = 0.722, SCD = 0.70, SCC = 0.707, SCMap = 0.714) exceeds the threshold of 0.5, further affirming the constructs' adequacy in explaining the variance of their

Table 1
Reliability and validity statistics.

Construct	Item	FL	AVE	CR	CB alpha	AVE (Sqrt)
Supply Chain Innovation Practices	SCIP1	0.71	0.52	0.916	0.74	0.722
	SCIP3	0.62				
	SCIP4	0.76				
	SCIP5	0.66				
	SCIP6	0.65				
	SCIP7	0.79				
	SCIP8	0.78				
	SCIP10	0.69				
	SCIP11	0.80				
	SCIP12	0.74				
Supply Chai Decarbonization	SCD1	0.65	0.5	0.9	0.77	0.70
	SCD2	0.62				
	SCD3	0.77				
	SCD4	0.71				
	SCD5	0.80				
	SCD6	0.66				
	SCD7	0.65				
	SCD9	0.64				
	SCD10	0.82				
Supply Chain Collaboration	SCC1	0.75	0.5	0.91	0.81	0.707
	SCC2	0.71				
	SCC3	0.68				
	SCC4	0.71				
	SCC5	0.66				
	SCC6	0.73				
	SCC7	0.75				
	SCC8	0.67				
	SCC9	0.63				
	SCC10	0.74				
Supply Chain Mapping	SCMap1	0.74	0.51	0.88	0.73	0.714
	SCMap2	0.81				
	SCMap3	0.72				
	SCMap4	0.62				
	SCMap5	0.69				
	SCMap6	0.62				
	SCMap7	0.65				
	SCMap8	0.82				
	SCMap9	0.66				
	SCMap10	0.70				
	SCMap12	0.65				
	SCMap13	0.76				
	SCMap14	0.77				
	SCMap15	0.72				

Deleted items: SCIP2, SCIP9, SCD8, SCMap11 indicators. The deletion of specific items (SCIP2, SCIP9, SCD8, SCMap11) suggests a rigorous process to refine the measurement model, ensuring that only items that significantly contribute to the constructs' reliability and validity are retained. This meticulous approach enhances the model's overall integrity, facilitating a more accurate and reliable assessment of the relationships between supply chain innovation practices and supply chain decarbonization, mediated by supply chain collaboration and mapping.

Table 2 presents the discriminant validity of the constructs based on the Fornell-Larcker criterion, which is crucial for ensuring that each construct in the study is distinctly different from the others. Discriminant validity is achieved when the square root of the Average Variance Extracted (AVE) for each construct (diagonal values in bold and italics) is greater than its highest correlation with any other construct. This criterion safeguards against the overlap of constructs, confirming that each captures a unique aspect of the phenomena under study.

For Supply Chain Innovation Practices (SCIP), the square root of AVE is 0.72, indicating that it shares more variance with its own indicators than with those of any other construct, as its correlations with SCD (0.6), SCC (0.42), and SCMap (0.26) are lower. Similarly, Supply Chain Decarbonization (SCD) demonstrates adequate discriminant validity, with a square root of AVE at 0.7, exceeding its correlations with SCIP (0.6), SCC (0.23), and SCMap (0.24). Supply Chain Collaboration (SCC) and Supply Chain Mapping (SCMap) also meet the Fornell-Larcker criterion, with square roots of AVEs at 0.7 and 0.71, respectively, which are higher than their correlations with other constructs.

The Variance Inflation Factor (VIF) values, ranging from 1.51 to 2.77, fall within acceptable limits, indicating no multicollinearity issues among the constructs. This confirms that each construct is measuring a distinct concept, further validated by the discriminant validity results. The successful demonstration of discriminant validity through the Fornell-Larcker criterion underscores the rigorous measurement validation process undertaken in this study, ensuring that the constructs are both reliably measured and distinctly different, thus facilitating accurate analysis of their interrelations.

The path analysis results are presented in Table 3. The path from SCIP to SCD (β 0.227, t-value 2.768) confirms that as SCIP has positive impact on the level of SC decarbonization. This finding underscores the l role of innovation practices in enhancing environmental sustainability in the supply chain. The relationship between SCIP and SC collaboration (β 0.114, t-value 1.511) demonstrates has not been substantiated, as evident from the insignificant t-value. Further, the path from SCIP to SC mapping (β 0.352, a t-value 7.154) is positive and significant. This highlights the significant role of SC innovation practices in promoting the adoption of SC mapping, a key enabler of more efficient and sustainable SCM. Further exploring the downstream effects, the path from SC collaboration to SC decarbonization (β 0.189, t-value of 2.719), indicates a positive and significant relationship. This suggests that SC collaboration among SC partners can be a valuable lever for achieving decarbonization goals. Additionally, the path from SC mapping to decarbonization (β 0.41, t-value 2.867) stands out as the most potent direct influence on SC decarbonization. This emphasizes the critical role of SC mapping in identifying and executing decarbonization strategies across the supply chain.

The adjusted R-square values show the moderate level of model fitness. Likewise, Q square value also confirm the predictive relevance of the model.

Table 2
Discriminant Validity based in Fornel -Larcker criteria.

	VIF	SCIP	SCD	SCC	SCMap
Supply Chain Innovation Practices (SCIP)	1.51	***0.72***			
Supply Chai Decarbonization (SCD)	2.77	0.6	***0.7***		
Supply Chain Collaboration (SCC)	1.89	0.42	0.23	***0.7***	
Supply Chain Mapping (SCMap)	2.46	0.26	0.24	0.37	***0.71***

Values in diagonal, bold and italics are square rooted values of AVE

Table 3
Path analysis.

	β	SE	t-value
SCIP → SC Decarbonization	0.227	0.082	2.768292683
SCIP → SC Collaboration	0.114	0.0754	1.51193634
SCIP– > SC Mapping	0.352	0.0492	7.154471545
SC Collaboration – > SC Decarbonization	0.189	0.0695	2.71942446
SC Mapping → SC Decarbonization	0.41	0.143	2.867132867
Adj R-Square	0.492		
Q (Predictive relevance)	0.186		

The results of the path analysis have been summarized in Table 4, to test the major hypothesis of the study. Hypothesis 1, which asserts that SCIP positively influences SC decarbonization, finds robust support through empirical evidence. The results in Table 4 (β 0.227 t-value 2.768) confirms a significant direct relationship, implying that firms improving SCIP are likely to witness enhancements in their SC decarbonization efforts. This underscores the pivotal role of SC innovation practices in propelling environmental sustainability in the SC framework.

However, Hypothesis 2 does not confirm this narrative. Hypothesis 2 tests whether SC collaboration serves as an effective mediator between SCIP and decarbonization efforts. Despite the anticipated synergies, the findings — reflected in Table 4 *(β 0.040, t-value 1.573)* — do not reach the threshold of statistical significance, leading to the hypothesis being unsupported. This suggests that the anticipated amplification of SCIP's impact on SC decarbonization through collaborative efforts among supply chain partners may not hold as strongly as presumed, although collaboration remains a valuable facet of SCM in other respects. Transitioning to Hypothesis 3, which tests the mediating role of SC mapping. The results (*β* 0.144, t-value of 5.011) lend robust support to the hypothesis, illustrating a significant mediating effect. This finding demonstrates the role of SC mapping as a pivotal mechanism for channeling SC innovation practices towards effective decarbonization strategies. It accentuates how SC mapping, by enhancing visibility and offering deeper insights into the supply chain, empowers firms to pinpoint and deploy targeted SC innovations that markedly drive decarbonization efforts.

Collectively, these findings illustrate a comprehensive picture of the relationship between SCIP, SCC, and SC mapping in improving SC decarbonization. While the direct influence of SCIP on SC decarbonization is evident and robust, the mediating effects reveal a more detailed interaction. SC Collaboration, though beneficial across various dimensions of SCM, exhibits limited mediation in linking SCIP with SC decarbonization. Conversely, SC mapping emerges as a critical facilitator, highlighting its strategic value in leveraging SCIP for achieving greater environmental sustainability in supply chains.

6.2. *Discussion*

Our findings from the hypotheses testing where echoes existing

Table 4
Hypotheses testing.

Hypothesis	β	t-value	Decision
Hypothesis 1*: SC Innovation practices improve SC decarbonization of a firm*	0.227	2.768	Supported
Hypothesis 2*: SC Collaboration mediates the relationship between SC Innovation practices and SC decarbonization of a firm*	0.040	1.573	Not Supported
Hypothesis 3*: SC Mapping mediates the relationship between SC Innovation practices and SC decarbonization of a firm*	0.144	5.011	Supported

literature and extends its understanding, there it contrasts with the literature on SC innovation, collaboration, mapping, and their collective impact on decarbonization efforts. The significant direct impact of SCIP on SC decarbonization, as supported by Hypothesis 1, echoes the assertions of numerous studies (e.g., Isaksson, R., Johansson, P., & Fischer 2010; Gao et al., 2017; Orji and Liu 2020; Yadav et al., 2023) that have highlighted the critical role of innovation in enhancing environmental sustainability in supply chains. This finding is consistent with the broader literature that posits innovation as a cornerstone for achieving operational efficiencies and environmental objectives. For instance, studies have shown that technological and process innovations can lead to reduced emissions and waste, thereby contributing to overall sustainability of a supply chain (De Marchi, 2012; Kusi-Sarpong et al., 2022; Mubarik et al., 2021).

However, the role of SCC as a mediator between SCIP and decarbonization, tested in Hypothesis 2, diverges notably from existing literature. Although supply chain collaboration is frequently highlighted as a crucial mechanism for enhancing sustainability outcomes through shared knowledge, pooled resources, and synchronized activities (Duong and Chong, 2020; Sudusinghe and Seuring, 2022; Wadood et al., 2022), this study found no significant mediation effect. Several potential explanations can provide deeper insights into this unexpected result. One plausible reason relates to the nature and depth of collaboration. Effective collaboration requires not only resource-sharing but also well-aligned strategic objectives and clearly defined roles and responsibilities (Kusi-Sarpong et al., 2024). Misalignment of sustainability goals among partners may weaken the potential benefits of SCIP, thus diminishing collaboration's mediating influence. Sudusinghe and Seuring (2022) underscore that successful collaboration for sustainability relies heavily on mutual understanding and compatible objectives, which might not have been sufficiently developed among the firms examined in this study. Additionally, prior research has identified inherent barriers within supply chain collaboration that could obstruct its effectiveness. These barriers include distrust, unequal power dynamics, and cultural or organizational differences (Khan et al., 2022; Andalib Ardakani et al., 2023). Firms operating in complex sectors like electrical and electronics often face these challenges intensely due to diverse stakeholder interests and geographically dispersed operations, which complicate effective collaboration. Similarly, the absence of significant mediation could also result from the indirect and incremental nature of collaboration's impacts on sustainability. Collaboration efforts might require a longer period to manifest tangible decarbonization outcomes, especially if partnerships are relatively new or still evolving in strategic maturity (Duong and Chong, 2020). Therefore, future research should consider longitudinal studies to better capture and understand the delayed effects and conditions under which collaboration becomes significantly impactful for supply chain decarbonization.

In contrast, the strong mediating role of SC mapping in the relationship between SCIP and decarbonization, as highlighted by Hypothesis 3, aligns with and extends the literature that underscores the importance of visibility and transparency in achieving sustainability goals. The study confirms and extends the findings of Mubarik et al. (2021), Khan et al. (2022) and Kusi-Sarpong et al. (2022). These studies strongly advocate the significant role of SC mapping in sustainability. They further argue that SC mapping facilitates a comprehensive understanding of the supply chain, enabling firms to identify critical points where interventions can yield significant environmental benefits. This finding resonates with the notion that informed decision-making, underpinned by detailed insights into SC operations, is pivotal for the effective implementation of sustainability initiatives. The contrast between the expected and observed mediating effects of collaboration and mapping respectively points to the complex dynamics of operationalizing sustainability practices in supply chains. It suggests that while SC collaboration provides a foundational platform for joint efforts, the targeted application of innovations for decarbonization may require the detailed insights that mapping uniquely offers.

The divergence between the observed findings and some aspects of the existing literature invites further investigation into the underlying reasons. Factors such as the specific industry context, the maturity of the supply chain, and the nature of the innovations considered could influence the effectiveness of collaboration and mapping as mediators. Additionally, the variance might be attributed to methodological differences, with the present study's focus on SCIP as a composite construct potentially capturing a broader range of innovation practices than those examined in prior research.

In short, the findings reveal both concordances and divergences that enrich our understanding of how theoretical concepts apply in practical scenarios, particularly in the context of supply chain sustainability.

7. Conclusion

The overarching objective of the study was to assess the direct impact of SCIP on decarbonization efforts and examine the mediating roles of SC collaboration and SC mapping in this process. Drawing upon data collected from Malaysian E&E sector, the research employed PLS-SEM for its analysis. The key findings of the study reveal a significant direct impact of SCIP on SC decarbonization, underscoring the vital role of innovation practices in driving environmental sustainability. However, the anticipated mediating role of SC collaboration was not supported, suggesting that the path from innovation to decarbonization does not necessarily amplify through collaborative efforts. In contrast, SC mapping emerged as a significant mediator, highlighting its importance in translating SCIP into effective decarbonization strategies. This interesting divergence from expectations suggests a bit different dynamic between these constructs, with SC mapping providing the actionable insights needed for targeted decarbonization interventions, whereas SC collaboration, though beneficial in various SC aspects, might not directly enhance the SCIP-decarbonization linkage. These findings show that despite the potential challenges and the initial costs associated with implementing SC innovations, the long-term environmental and economic benefits are substantial. SCIP, when strategically implemented, can lead to significant reductions in carbon emissions by optimizing logistics, enhancing resource efficiency, promoting the use of renewable energy, and fostering a circular economy. Moreover, as consumer awareness and demand for sustainable products increase, companies that proactively decarbonize their supply chains through innovative practices are likely to gain a competitive edge in the market.

The major contribution of this study lies in its comprehensive examination of the roles that SCIP, collaboration, and mapping play in the decarbonization of supply chains, particularly within the context of the Malaysian E&E sector. By employing a robust methodological approach and drawing upon a significant body of literature, the research not only validates the direct impact of SCIP on decarbonization but also uncovers the nuanced mediating effects of collaboration and mapping. This provides valuable insights into the mechanisms through which innovation practices can be effectively translated into environmental sustainability outcomes. The findings of the study contribute to the theoretical discourse on supply chain sustainability by highlighting the critical role of SC mapping in mediating the relationship between SC innovation practices and decarbonization. This extends the existing literature, which has predominantly focused on the positive aspects of SC collaboration, by demonstrating that the specificity and actionable insights offered by mapping are pivotal for achieving decarbonization goals. Furthermore, the research sheds light on the complex dynamics of operationalizing sustainability practices within supply chains, offering a nuanced understanding of how different elements interact to drive environmental objectives.

Conclusively, by emphasizing the importance of SCIP and the strategic role of supply chain mapping, the research provides a clear pathway for companies to enhance their decarbonization efforts. Additionally, the findings suggest that while collaboration remains a valuable aspect of supply chain management, firms should also focus on developing robust mapping capabilities to identify and implement targeted innovations for sustainability.

7.1. Implications

The study has some key implications for managers. First, the significant role of SCIP in SC decarbonization underlines the critical role of innovation in environmental sustainability efforts. It shows that the integration of innovative practices into their SC operations can lead to significant improvements in decarbonization. This further suggests that an investment in SCIP, such as adopting new technologies, optimizing processes for energy efficiency, or utilizing sustainable materials, is not merely a cost center but a strategic initiative that can enhance environmental performance and, potentially, competitive advantage. Given the increasing global focus on sustainability, firms that lead in SCIP could benefit from improved brand image, customer loyalty, and alignment with international environmental standards, potentially opening new markets and opportunities. Further, the findings regarding the mediating role of supply chain collaboration offer a more complex perspective. Contrary to expectations, collaboration did not significantly mediate the relationship between SCIP and decarbonization. This does not diminish the value of collaboration in supply chain management but suggests its impact on SC decarbonization through SC innovation might not be as straightforward as previously assumed. Firms could thus approach SC collaboration with a clear strategy, focusing on partnerships that directly support their sustainability and innovation goals. Collaborative efforts should be structured with clear objectives, mutual benefits, and shared responsibilities towards achieving specific decarbonization targets. This implies a need for rigorous partner selection, transparent communication, and shared KPIs related to environmental sustainability. Further the significant role (mediating) of supply chain mapping stands out as a crucial finding for managerial consideration. This underscores the importance of visibility and detailed understanding of the supply chain for effective decarbonization. Firms are advised suggested to invest in SC mapping tools and practices to gain a comprehensive overview of their operations, identify high-impact areas for decarbonization efforts, and monitor the progress of these initiatives. Mapping can enable firms to pinpoint inefficiencies, assess the carbon footprint of different segments of their supply chain, and implement targeted innovations for improvement. Additionally, mapping can facilitate better risk management by identifying potential vulnerabilities in the supply chain that could affect sustainability goals, thereby allowing for more informed decision-making and strategic planning.

Putting together, our findings suggests that firms could adopt a multifaceted approach to supply chain sustainability, integrating SCIP with a strategic focus on mapping and selective collaboration. The strategic implementation of SC mapping, in particular, appears to be a critical enabler of effective decarbonization strategies. This approach Could be complemented by fostering a culture of innovation within the organization and across its supply chain networks to continuously seek and implement practices that enhance environmental sustainability.

7.2. Limitations and future research directions

The study has some limitations, which pave the way for future researchers. The focus of the study is Malaysian Electrical and Electronics (E&E) sector, which may be limited by its specific geographical and industry context. This limitation suggests the findings might not universally apply across different regions or industries with their own unique environmental, regulatory, and supply chain dynamics. Further research could broaden the scope to various locations and sectors to validate the study's applicability. Another notable limitation is the use of cross-sectional data, capturing only a momentary snapshot of the relationships between SCIP, SCC, SC mapping, and SC decarbonization, without accounting for their evolution over time. Longitudinal studies are recommended to explore these dynamics, offering a deeper causal understanding. The study predominantly employs quantitative methods, leaving unexplored qualitative aspects such as the motivations, challenges, and mechanisms underlying SCIP and its impact on SC decarbonization. Qualitative approaches like case studies could provide a richer, more detailed exploration of these aspects. Additionally, the unexpected results concerning the mediation role of SC collaboration hint at unseen moderating factors and the diverse impacts of different types of innovation practices on supply chain sustainability, indicating areas for future exploration. Last but not the least, the increasing role of digital technologies in enhancing supply chain management efficiency and sustainability—*such as blockchain, IoT, and AI*—presents a promising avenue for future research. These technologies could significantly improve SC transparency, traceability, and sustainability efforts, underscoring the need for further investigation into their potential to facilitate SCIP, refine SC mapping, and streamline collaboration.

CRediT authorship contribution statement

Muhammad Shujaat Mubarik: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Angappa Gunasekaran:** Visualization, Validation, Supervision, Methodology. **Sharfuddin Ahmed Khan:** Writing – review & editing, Conceptualization. **Muhammad Faraz Mubarak:** Validation, Data curation.

Declaration of competing interest

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

Acknowledgement

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Appendix-A. Questionnaire

Supply Chain Innovation Practices (SCIP)		1	2	3	4	5
SCIP1	Our supply chain strategies are closely aligned with our overall business goals and objectives.					
SCIP2	Our firm adopts the latest technologies (e.g., AI, IoT, blockchain) to enhance supply chain operations.					
SCIP3	We continuously innovate our supply chain processes based on customer feedback and market demands.					
SCIP4	Decision-making in our supply chain is heavily influenced by data analytics and predictive modeling.					
SCIP5	We employ innovative practices for risk identification, assessment, and mitigation in our supply chain.					
SCIP6	Sustainability and eco-friendly practices are integrated into our supply chain innovation efforts.					
SCIP7	There is a strong culture of collaboration and partnership with suppliers, customers, and other stakeholders in our supply chain.					
SCIP8	Our supply chain practices support and enhance innovation in product development and lifecycle management.					
SCIP9	There is a strong emphasis on continuous improvement and learning in our supply chain management practices.					
SCIP10	Advanced analytics are integrated into our supply chain for enhancing efficiency and performance.					

(*continued on next page*)

(*continued*)

Supply Chain Innovation Practices (SCIP)		1	2	3	4	5
SCIP11	Our supply chain is highly responsive to external forces such as economic changes, geopolitical events, and environmental concerns.					
SCIP12	Our supply chain can quickly adapt to market changes and unexpected disruptions.					
Supply Chain Decarbonization (SCD)						
SCD1	Our organization has achieved a measurable reduction in GHG emissions from supply chain operations compared to the previous year.					
SCD2	The organization has made significant progress towards its long-term decarbonization targets for the supply chain.					
SCD3	Our supply chain partners (e.g., suppliers, logistics providers) have demonstrated measurable progress in their decarbonization efforts.					
SCD4	The overall supply chain resilience against carbon-related risks (e.g., carbon pricing, regulations) has improved.					
SCD5	Our organization has engaged in carbon offsetting projects that effectively compensate for the emissions we cannot yet eliminate.					
SCD6	Energy efficiency improvements across our supply chain operations have resulted in significant carbon emissions reductions.					
SCD7	We have implemented circular economy practices (e.g., recycling, reusing materials) that have led to a reduction in carbon emissions.					
SCD8	Our supply chain has successfully transitioned a significant portion of our transportation to low-carbon alternatives (e.g., electric vehicles, rail).					
SCD9	The carbon footprint per unit of product shipped has decreased in the last 12 months.					
SCD10	We have significantly increased the use of renewable energy sources within our supply chain operations.					
Supply Chain Collaboration (SCC)						
SCC1	Our firm actively shares information and data with supply chain partners to improve transparency and efficiency.					
SCC2	The collaboration with our supply chain partners has led to improved business outcomes for our firm.					
SCC3	Our collaboration with supply chain partners includes efforts to promote sustainability and ethical practices across the supply chain.					
SCC4	We have formal agreements in place with our supply chain partners that define the scope and expectations of our collaborative efforts.					
SCC5	Our firm and supply chain partners regularly review and adjust collaboration practices to improve supply chain performance.					
SCC6	We participate in collaborative problem-solving activities with our supply chain partners to address operational challenges.					
SCC7	Our firm utilizes advanced technologies (e.g., IoT, AI, blockchain) for enhancing collaboration and efficiency within the supply chain.					
SCC8	We engage in joint strategic planning sessions with our supply chain partners to address long-term challenges and opportunities.					
SCC9	Our firm and its supply chain partners have aligned objectives and work towards common goals.					
SCC10	We have established trust-based relationships with our supply chain partners that facilitate open communication and mutual support.					
Supply Chain Mapping (SCMap)						
SCMap1	We are able to trace the supply chain back to the extraction or initial production stages for key materials.					
SCMap2	We have visibility into the capacity and operational status of all our manufacturing entities within the supply chain.					
SCMap3	Our supply chain mapping efforts facilitate effective collaboration and information sharing among different manufacturing entities.					
SCMap4	We regularly evaluate and optimize production schedules and processes with our manufacturing partners to improve efficiency.					
SCMap5	Our organization has a clear understanding of all manufacturing processes and flows within our supply chain.					
SCMap6	Our organization has established partnerships with upstream suppliers to ensure transparency in sustainability practices.					
SCMap7	We actively manage and mitigate risks associated with resource scarcity by having a detailed understanding of our upstream supply chain.					
SCMap8	We regularly assess the sustainability practices and ethical standards of our raw material suppliers.					
SCMap9	Our organization has comprehensive visibility into the origins of all raw materials used in our products.					
SCMap10	Our organization has complete visibility into the distribution and retail networks for our products.					
SCMap11	Our organization leverages downstream supply chain mapping to enhance the reliability and responsiveness of our delivery systems.					
SCMap12	Our downstream supply chain mapping provides insights into customer experiences and satisfaction levels.					
SCMap13	We actively monitor and optimize the efficiency of our product delivery systems to end consumers.					
SCMap14	We have strategies in place to address bottlenecks and improve service levels within our distribution process.					
SCMap15	Our midstream supply chain mapping identifies and addresses quality control measures across all manufacturing stages.					

Data availability

Data will be made available on request.

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