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Achieving Carbon Neutrality: Strategic Pathways to Sustainability and Net Zero in Manufacturing Supply Chains

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ABSTRACT

Reaching global net-zero targets has become an urgent priority as businesses and nations face increasing pressure to reduce greenhouse gas emissions. Achieving carbon neutrality in manufacturing supply chains requires comprehensive systemic changes across business processes. It demands forward-looking strategies that guide companies toward long-term sustainability and net-zero objectives. While earlier research has identified several drivers and barriers, there remains a lack of clear, actionable roadmaps that companies can follow. This paper fills this research gap by determining 11 interdependent strategies and grouping them into six levels of hierarchy and discovering that they play the roles of driving and dependent. Results showed that important strategies consist of policy development and incentives, carbon accounting, collaborative learning, renewable energy adoption, low-emission transportation, digitalization, and circular practices. Using expert insights and a multi-round Delphi technique, the study identifies key strategies, which are then organized through total interpretive structural modeling (TISM) and cross-impact matrix-multiplication applied to classification (MICMAC) analysis. Results identify a pathway roadmap where strategies connect, allowing businesses to focus on initiatives including circular practices, digitalization, and waste reduction. Policy and incentives serve as essential tools, with companies responsible for turning concepts into key performance indicators. Our research offers a blueprint for global organizations to better align efforts, lower emissions, and work toward net-zero. It outlines the relationship among the strategies and priorities needed by global companies and governments to develop effective cross-border collaboration and coordinate sustainability efforts, thus supporting climate change commitments.

1 | Introduction

The fight against climate change demands rapid, systemic, and large-scale reductions in carbon emissions, with manufacturing being one of the biggest contributors to global greenhouse gas emissions (Geng et al. 2025). Net-zero is no longer a distant target; it has become an operational and strategic necessity because it is the only viable way to stabilize our climate and avoid the worst effects of climate change. Significantly, companies are beginning to be measured not only by their carbon disclosure or transparency in reporting but also by whether they can prove they have operationalized carbon neutrality throughout production, sourcing, logistics, and end-of-life across their supply chains (Belhadi et al. 2024). Moreover, although the economy undoubtedly represents one of the most important strengths of sustainability in the production paradigm, the impact of green technology as a supply side lever and that of responsible consumption as a demand side driver should not be underestimated either (Dwivedi et al. 2023). Carbon neutrality goals usually include clear targets to cut emissions as much as possible and offset any excess emissions through strategies such as carbon capture, adopting renewable energy, or reforestation (Patil et al. 2024; Wu et al. 2025). For example, Microsoft's commitment to reach carbon negative emissions by 2030 involves both supplier engagement efforts as well as internal carbon pricing, which forces suppliers upstream to become more carbon efficient. IKEA, in their announcement to reach climate positive by 2030, have had to redesign their entire supply chain, including a circular material sourcing strategy, low-carbon transport logistics, and supplier decarbonization programming (Kv et al. 2025). These examples highlight how carbon neutrality will soon be considered at the supply-chain level as opposed to at the firm level.

The rise in climate-related risks, such as extreme weather events and biodiversity loss, has increased the urgency for coordinated net-zero efforts (Climateseed 2025). Reflecting this need, many countries have committed to reaching net zero through a combination of policies and technologies that balance emitted carbon with removing it from the atmosphere (Kannan et al. 2022). For instance, during the 2019 United Nations Climate Action Summit, more than 66 countries pledged to achieve net-zero emissions, with an additional 61 nations later joining to reach this goal by 2050 (UNFCCC 2019). Bhutan and Suriname are early examples of countries achieving carbon neutrality (Zhao et al. 2022), while China, the United States, and India have set their respective net-zero timelines for 2060, 2050, and 2070 (Solanki et al. 2024). Nonetheless, the UN Environment Programme (UNEP) has indicated that actions to date fall short of what is required to achieve COP26 targets. There is still a gap between what countries and companies are promising and what they are actually doing on the ground to improve their industrial supply chains (Yu et al. 2025).

In this context, the current study targets the manufacturing sector of India as it contributes towards growth, as well as a major share of national emissions. Moreover, the sector is expected to achieve a worth of US$1 trillion by 2025 and create more than 90 million jobs, indicating its strategic significance (Datta 2024). Government policy support, combined with technological advancements, enables sustainable manufacturing to progress in India (Bansal 2025). The declaration at COP26 of the nation's pledge to reach net-zero emissions by 2070 demands specific approaches to merge carbon neutrality in manufacturing (Solanki et al. 2024). Several Indian companies have also taken proactive steps. For example, Tata Steel has set a goal to achieve net-zero emissions by 2045,[1] while Mahindra & Mahindra has pledged carbon neutrality by 2040,[2] aligning their operations with the national target while addressing global supply chain pressures. As a potential global production hub, India stands well-prepared to utilize environmental regulations for economic growth and knowledge advancement opportunities. India's 4th Biennial Update Report (BUR-4) indicates a 7.93% decrease in GHG emissions during 2020 compared with the previous year.[3] India thus shows its dedication to building a future that supports environmental sustainability and climate resilience.

Businesses face mounting pressure to implement sustainable practices as consumers, retailers, and supply chain partners demonstrate increasing environmental consciousness (Bataille et al. 2021). The transition to sustainable practices faces difficulties because of technological and market uncertainties; these demand advanced capabilities and coordinated stakeholder support from government bodies alongside industry and society at large (Zhou et al. 2021). The Indian government's policies and regulatory measures play an essential role in advancing engineering solutions toward carbon neutrality as India targets carbon neutrality by 2070.[4]

In spite of increasing international interest, research on carbon neutrality in manufacturing supply chains is piecemeal in nature (Zhao et al. 2022; Do et al. 2023). Current studies typically focus on barriers, drivers, or technological enablers (Dwivedi et al. 2023; Patil et al. 2024; Wu et al. 2025), but these studies fail to demonstrate how strategies interact or sequentially develop over time to achieve net zero (Belhadi et al. 2024). For instance, the research of Dwivedi et al. (2023) has provided a thorough assessment of the drivers behind sustainable manufacturing. However, these assessments are mainly descriptive in nature, with limited depth into several motivation attributes; they also lack any type of framework for developing actions that create pathways towards carbon-neutrality or net-zero outcomes. Likewise, even though studies regarding carbon reduction strategies specific to particular sectors helped discover contextual relationships and hierarchy between carbon reduction strategies (e.g., analysis of the leather supply chain in Bangladesh through TrF-WINGS and ISM) (Moktadir and Ren 2025), these studies were limited to specific sectors without providing roadmaps that can be generalized to firms in the manufacturing sector.

Unlike previous studies that have focused solely on carbon footprint measurements and analyses, this research creates a structured, comprehensive roadmap for performing real-world implementations of carbon-neutral or net-zero manufacturing supply chain strategies, utilizing multi-sectoral input and interdependent, hierarchical strategic development to assist in practical implementations. Therefore, managers and policymakers do not have a forward-looking roadmap to assist them in designing interventions that respond to short-term pressures while, at the same time, advancing carbon neutrality (Yu et al. 2025). These gaps highlight the need for a study that not only identifies the appropriate strategies but also explains their interdependence and influence pathways. To fill these research gaps, the present research formulates the following research questions:

RQ1. What are the key forward-looking strategies that businesses must adopt to achieve carbon neutrality in manufacturing supply chains?

RQ2. How do these strategies interact, and how can they be structured into a forward-oriented framework that guides businesses toward net-zero targets?

This study adds to the existing knowledge on sustainability transition and the concept of net-zero supply chains via a novel and integrated methodological approach for structuring the complex interdependencies that exist between various strategic elements involved in sustainability transition/creating net-zero supply chains. Instead of looking at net-zero strategies as simply independent enablers, this study combines the Delphi method with total interpretive structural modeling (TISM), as well as cross-impact matrix multiplication applied to classification (MICMAC), to create a theoretical framework that illustrates how different strategies interact with, support, and hierarchically affect each other. On one hand, the Delphi-based consensus validates the recommended strategies based on the knowledge and experience of practitioners. On the other hand, TISM analysis provides an explanatory perspective to theory development through the identification of causal relationships and multilevel dependencies between the strategies. MICMAC analysis further assists in identifying the cause-and-effect strategies that facilitate the dynamic classification of strategies. This analysis framework is relatively novel in the context of net-zero and sustainable supply chain literature.

The research presents a road map that is well-structured, relational, and phased, and utilizes multiple streams of data combined (qualitative and quantitative) to provide an outline for transitioning to net-zero. This adds to current literature by demonstrating the interaction between policy mechanisms, digitalization, circular behaviors, and operating interventions and how they co-evolve within the supply chains of emerging market countries. As such, this research makes an important theoretical contribution to the development of an operationalized Systemic Transition Logic and an important applied contribution through the establishment of a replicable analytical framework for global researchers and practitioners to use in other sustainable driven transformation projects.

The following structure is adopted for the remainder of the paper. Section 2 offers an in-depth literature review, followed by the research methodology in Section 3. Section 4 presents the development of the model, while the findings of the study are discussed in Section 5. Furthermore, Section 6 discusses the implications of research, and Section 7 draws conclusions of the study and indicates limitations and possible future research avenues for the development of the work.

2 | Literature Review

2.1 | Carbon Neutrality

The pressing global need to achieve carbon neutrality has escalated because of increased GHG emissions resulting from industrial growth, urban expansion, and greater use of fossil-fuel-based energy systems (Sindhwani et al. 2022; Geng et al. 2025). The majority of current energy requirements depend on carbon-heavy sources, which intensify climate change problems. To address the resulting environmental challenges, sustainable production and consumption practices are recommended while industries adopt carbon-neutral strategies to mitigate emissions (Waisman et al. 2019). The European Parliament suggests that "carbon neutrality is reached when the same amount of CO_2 is released into the atmosphere as is removed by various means, leaving a zero balance, also known as a zero-carbon footprint".[5] In the industrial context, "carbon neutrality refers to a condition in which, after having adopted measures to reduce its emissions, a company compensates for the residual and unavoidable ones through offsetting projects to arrive at a zero net balance".[6]

The 26th UN Climate Change Conference (COP26) triggered worldwide attention by underlining the importance of carbon neutrality in governmental and corporate approaches. Climateseed (2025) highlights that climate-related disasters have become more frequent, which has led to increased urgency. For supply chains to achieve carbon neutrality, they must minimize or offset emissions throughout all phases from raw material acquisition through product distribution to final disposal (Belhadi et al. 2024). Although it is difficult to determine an accurate percentage, past studies conclude that a significant quantity of emissions is closely linked with supply chains around the world (Vimal et al. 2022; Yu et al. 2025).

Organizations are now joining initiatives such as the Carbon Disclosure Project, Science-Based Targets initiative (SBTi), and environmental product declarations to improve their transparency and accountability (Dohale, Ambilkar, et al. 2024). Taken together, these efforts suggest a reframing of emission concerns from the level of the firm to responsibility through supply chains, although uptake differs by sector and geography. Firms are often compelled to respond to these initiatives due to external stakeholders such as regulators, investors, and customers pushing for involvement (Sprengel and Busch 2011; Yunus et al. 2020). While involvement in these initiatives is becoming more prevalent, firms still struggle to act on commitments and meet targets in a manner that is cohesive and quantifiable throughout supply chains.

2.2 | Status of Carbon Neutrality Initiatives in the Manufacturing Supply Chain

Research has expanded significantly to investigate carbon-neutral routes and the barriers and drivers within manufacturing supply chains. At the global level, Mahapatra et al. (2021) investigate Scope 1, 2, and 3 emissions within multiple industrial sectors, showing that neglecting value-chain emissions makes net-zero targets unattainable. Chen et al. (2022) present a detailed analysis of how COP26 commitments have led to fundamental changes in both national strategies and industrial practices. More recently, Gu and Zhao (2025) reveal essential insufficiencies in carbon data transparency, which acts as a major barrier to organizational climate action. New approaches have been created to assist different industries in reducing their carbon emissions. For example, O'Keeffe et al. (2023) have launched a simulation-based carbon accounting tool designed for Irish manufacturers, while Lee and Hussain (2024) investigate supply chain actors' strategic responses to carbon pricing and cap-and-trade systems in China. From a technological standpoint, Bhatia et al. (2024) and Patil et al. (2024) demonstrate how Industry 4.0 technologies such as blockchain, Internet of Things (IoT), and artificial intelligence (AI), can make real-time carbon tracking and performance benchmarking possible. Shaik et al. (2024) emphasize the importance of AI technologies in helping small and medium-sized enterprises (SMEs) to progress towards sustainability and carbon neutrality. Unger and Nippa (2024) conclude that only a few firms have adopted climate neutrality strategies (CNS) in the European Union, where the focus has been on actively minimizing emissions at the firm level. Research conducted in parallel explores the uptake of advanced solutions in decarbonization. For example, Bhatia et al. (2025) highlight the drivers for European firms adopting carbon capture, utilization, and storage (CCUS) in emission-intensive industries, while Li, Zhu, et al. (2025) show that supply chain ecocentricity mediates the relationship between digitalization and carbon performance in Chinese firms. These are just some examples of the role of digital transformation in carbon-neutral supply chains. The body of research in India remains at an early stage yet continues to develop with increasing complexity. Dohale, Ambilkar, et al. (2024) implement a two-step fuzzy Analytical Hierarchy Process (AHP)—Interpretive Structural Modeling (ISM) framework to determine the essential success factors for achieving carbon-neutral manufacturing in India. Another study by Dohale, Kamble, et al. (2024) utilizes the Voting Analytical Hierarchy Process (VAHP)-Bayesian Network model in the textile sector to demonstrate the critical roles of regulatory support and supply chain coordination. Solanki et al. (2024) introduce a Delphi–fuzzy Best-Worst Method (BWM)–Weighted Influence Non-linear Gauge System (WINGS) evaluation method for the drivers of carbon regulation in Indian manufacturing firms. Singh et al. (2025) deploy Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine the role of digital technologies in making the environment more sustainable and enhancing operational efficiency in the push towards carbon neutrality. Some recent studies, such as Bansal (2025), suggest that decarbonization technology adoption accelerates through regulatory frameworks, which serve as vital components for India's net-zero emissions target by 2070.

Such pressures are not only regulatory but also reputational. Geng et al. (2025) show that manufacturing companies are exposed to stakeholder pressures from regulators, investors, and consumers, encouraging these companies to visibly reduce emissions in their value chains. Nonetheless, some research also notes that companies tend to focus their efforts on improving their internal operations and miss out on firm-wide coordination across the supply chain (Plambeck 2012; Belhadi et al. 2024). This causes limited effectiveness of carbon neutrality efforts, especially when there are multiple tiers in a supply chain. In general, while there are many existing studies that discuss technologies, policies, and enabling factors, the body of knowledge is still disjointed and lacks cohesion. There are a few studies that look at drivers and barriers in isolation, and a few that provide a logical and sequenced path forward for implementation throughout manufacturing supply chains. This issue is particularly relevant to emerging countries like India, where individual efforts are being taken up by firms, for example, renewable energy integration, clean logistics, and circular initiatives, however, without a prescription on how they can be orchestrated and scaled up holistically. Hence, research efforts are needed that can transcend this gap of disjointed analysis and provide an integrated perspective towards achieving a carbon-neutral transition in manufacturing supply chains.

Table 1 suggests that most research on carbon neutrality in supply chains is concentrated in China and other developed countries; these nations contribute heavily to global emissions and have made strong net-zero commitments (Mahapatra et al. 2021; Bai et al. 2022; Zhang, Jin, and Wang 2023; Bhatia et al. 2024; Li, Zhu, et al. 2025). These studies use a variety of methods, such as BWM, DEMATEL, regression, and simulation, to look at barriers, drivers, and performance impacts in different manufacturing sectors (Kannan et al. 2022; Singh et al. 2025; Li, Zhu, et al. 2025). However, the literature is still fragmented, often looking at enablers or barriers instead of giving a structured pathway for adopting strategies. More importantly, very few studies explain how these strategies interact or unfold over time, which leaves a clear gap in understanding how manufacturing supply chains, especially in developing countries like India, can actually move step by step toward carbon neutrality.

India has developed multiple interesting initiatives and policy frameworks, such as the National Green Hydrogen Mission, the Green Steel Mission, and decarbonizing roadmaps for hard-to-abate sectors (like steel and cement).[7] These initiatives show an increased commitment to incorporating carbon neutrality into the manufacturing supply chain. Firms are also beginning to introduce chain-level actions. For instance, IPM India is shifting its logistics to EVs/CNG vehicles and is planning to shift some modal transportation from air freight to sea/land.[8] Despite this progress, literature demonstrates that many of these actions are still piecemeal: no widely accepted, structured pathway shows how multiple strategies need to be sequenced, and how firms in India can incrementally scale up from enabling mechanisms (e.g., renewable energy, clean logistics) to full supply chain transformation.[9] Existing efforts suffer from this disconnect, hindering their impact and scalability.

This study aims to bridge these gaps by providing a comprehensive, actionable framework that amalgamates fragmented approaches into a cohesive step-by-step guide for carbon neutrality in manufacturing supply chains. In doing so, the research offers prescriptive advice for firms based in developing markets like India about how to move from enabling actions to complete decarbonization of their supply chains.

3 | Research Methodology

This study's key objective is to determine strategies to achieve carbon neutrality in the supply chain of manufacturing industries. It also develops a structural model that sets up relationships among the strategies. To meet this objective, this research uses a mixed-method research strategy whereby the steps are sequential and integrated. Firstly, the literature review is utilized to build a theoretically sound but initial list of strategies, which are further modified and validated via expert opinions through the Delphi method. The validated strategies act as the only input for TISM so that a comprehensive interpretive causal structure depicting both direct and transitive relationships, along with logic, can be developed. Next, MICMAC analysis is employed to validate the results obtained through TISM by providing structural validation and role differentiation. Through the sequential dependence and functional complementarity created by an "integrated approach", the fragmented and non-causal knowledge generated by TISM can be organized into a single causal-based decision-making model. This integrated approach creates a

TABLE 1 | Highlights of key studies on carbon neutrality in manufacturing supply chains.

Source	Context	Methodology	Key contribution
Bhatia et al. (2025)	EU	Grounded Theory	Identifies organizational drivers and barriers affecting CCUS adoption across high-emission industries.
Singh et al. (2025)	India	Partial Least Squares Structural Equation Modeling (PLS–SEM)	Shows how digital transformation enhances green supply chain efficiency and circular economy adoption.
Li, Zhu, et al. (2025)	China	Regression and Bootstrap	Demonstrates the positive effect of supply chain digitalization on carbon performance using NRBV.
Bhatia et al. (2024)	US & UK	Gioia Method	Explores drivers, barriers, and mitigation strategies for digital technology adoption toward carbon neutrality.
Lee and Hussain (2024)	China	Simulation and DOE	Optimizes producer–intermediary–retailer decisions to minimize CO_2e in regional supply chains.
Patil et al. (2024)	India	Best-Worst method (BWM) and Modified TISM	Develops a hierarchical framework for technology adoption in smart, carbon-neutral supply chains.
Dohale, Ambilkar, et al. (2024)	India	Strong Ordering Data Envelopment Analysis (SODEA) and Bayesian Network (BN) methods	Identifies critical lean and sustainable innovation factors for carbon-neutral manufacturing.
Dohale, Kamble, et al. (2024)	India	Voting Analytical Hierarchy Process (VAHP) and Bayesian Network (BN) method	Determines and forecasts key determinants of carbon neutrality in the clothing sector.
Shaik et al. (2024)	USA	PLS-SEM	Examines AI-driven business model innovation as a mediator toward carbon-neutral SMEs.
Unger and Nippa (2024)	EU	Descriptive Data Analysis and Multiple Logistic Regression	Tests firm-level factors influencing climate neutrality strategy adoption.
Chen and Chung (2023)	China	Data Envelopment Analysis (DEA)	Assesses supplier sustainability performance toward carbon neutrality using a phased DEA approach.
Do et al. (2023)	Vietnam	BWM and Goal Programming	Develops a circular economy index for carbon neutrality in rubber and wood industries.
O'Keeffe et al. (2023)	Ireland	Mathematical Modeling	Proposes a decision-support tool for carbon-neutral manufacturing transitions.
Zhang, Tay, et al. (2023)	UK, Bulgaria, Pakistan	Case Studies	Identifies drivers of carbon neutrality and its impact on supply chain performance.
Zhang, Jin, and Wang (2023)	China	Game Theory	Analyses subsidy effects on emissions reduction and manufacturing cost.
Bai et al. (2022)	China	Multi-objective Optimization	Optimizes supplier selection and order allocation for carbon-neutral supply chains.
Fan et al. (2022)	China	Artificial Neural Network (ANN)	Predicts long-term carbon emission drivers to support national carbon neutrality goals.

(Continues)

TABLE 1 | (Continued)

Source	Context	Methodology	Key contribution
Kannan et al. (2022)	India	Best Worst Method (BWM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL)	Identifies barriers to implementing carbon regulatory policies in supply chains.
Zhao et al. (2022)	China	Theoretical Analysis	Compares China, US, and EU pathways toward carbon neutrality.
Mahapatra et al. (2021)	UK	Regression Analysis	Links carbon footprint reduction to firm financial performance.
Zameer et al. (2021)	China	Structural Equation Modeling (SEM)	Examines how environmental orientation and eco-innovation improve environmental performance.

causal-based model that has been empirically validated. This outcome cannot be accomplished by using these methodologies independently of one another.

The methodological novelty of this study stems from how we came to combine multiple approaches that were previously considered independent and/or additive into one coherent method, rather than utilizing them separately. Each approach within this meta-method serves a specific epistemic objective (i.e., identification, validation, causal explanation, and structural positioning). In addition, all methods depend on the outputs produced during the previous step. As a result, the complete methodology is able to function as an integrated system of inquiry, rather than as a collection of distinct tools.

Figure 1 presents the three-phased research approach adopted in this study. A systematic literature review (SLR) approach is used to find the strategies to be adopted to meet carbon neutrality goals. Recognized scholarly databases, Web of Science, Scopus, Google Scholar, and EBSCO, are repeatedly explored to identify relevant research articles.

The following keyword clusters are used to search research articles: (i) relevant to carbon neutrality goals in manufacturing supply chain, such as "carbon neutrality", "climate neutrality", "carbon neutrality in the supply chain", "carbon neutrality goals", "net zero emission", "net-zero"; (ii) relevant to strategies to accomplish carbon neutrality goals as "strategies", "practices", "key strategies", "carbon neutrality strategies", "strategies for net zero emissions", "strategies for carbon neutrality goals" etc. in the article search field of abstract, title and keywords. The Boolean operators (OR/AND) are utilized to merge keyword clusters. The operator OR is used to combine keywords from the identical cluster, whereas the AND operator is utilized to combine keywords from the dissimilar cluster. The detailed process of performing SLR is demonstrated in Figure 2.

3.1 | Phase 1—Delphi Method

The strategies identified initially through the literature review are validated by conducting a Delphi study. In contrast with other approaches, such as surveys that may be employed for a study, the Delphi technique is a powerful method for an intensive investigation of resource experts (Wrålsen et al. 2021). It is distinguished by repetition, statistical collective efforts, regulated response, and facelessness. Because of these features, it prevents thinking as a group and allows experts to express their opinions freely. The expert group achieves a consensus amidst numerous meetings or frequent surveys. During each iteration, the gathered opinions are summated and handed over to the group for further examination (Viles et al. 2022) to permit the experts to re-examine their initial opinions on the topics suggested. Because of its iteration capacity, there is an additional benefit to this approach.

3.2 | Phase II—TISM

A lot of alternative multi-criteria decision-making (MCDM) approaches are available to analyze interactions among the factors; these include ANP, AHP, and Decision-Making Trial and Evaluation Laboratory (DEMATEL). Most approaches do not provide a model with hierarchical interrelationships among the factors. In contrast, the DEMATEL approach is competent in explaining the causal relationship between factors but lacks the development of a hierarchical structure with factors (Hashemi Petrudi et al. 2024).

On the other hand, TISM is a progression on traditional interpretive structural modelling (ISM); ISM is based on graph theory, where it transforms the conceptual models that are articulated poorly with vague relationships into complete models with an explicit linkage between factors (Mohaghegh and Größler 2024). Nevertheless, ISM has been criticized due to its limitations, such as narrow interpretations of potential links between the factors (Sorooshian et al. 2023) and omitting the transitive links. To overcome the limitations of ISM, TISM has been developed to depict the interrelationships among factors through both direct and transitive (indirect) links, highlighting the inherent logic behind the interrelationships (Kayikci et al. 2021). These advantages over other MCDM techniques result in the selection of a TISM approach for this study; however, a choice must also be made between the TISM and modified TISM (m-TISM) approach.

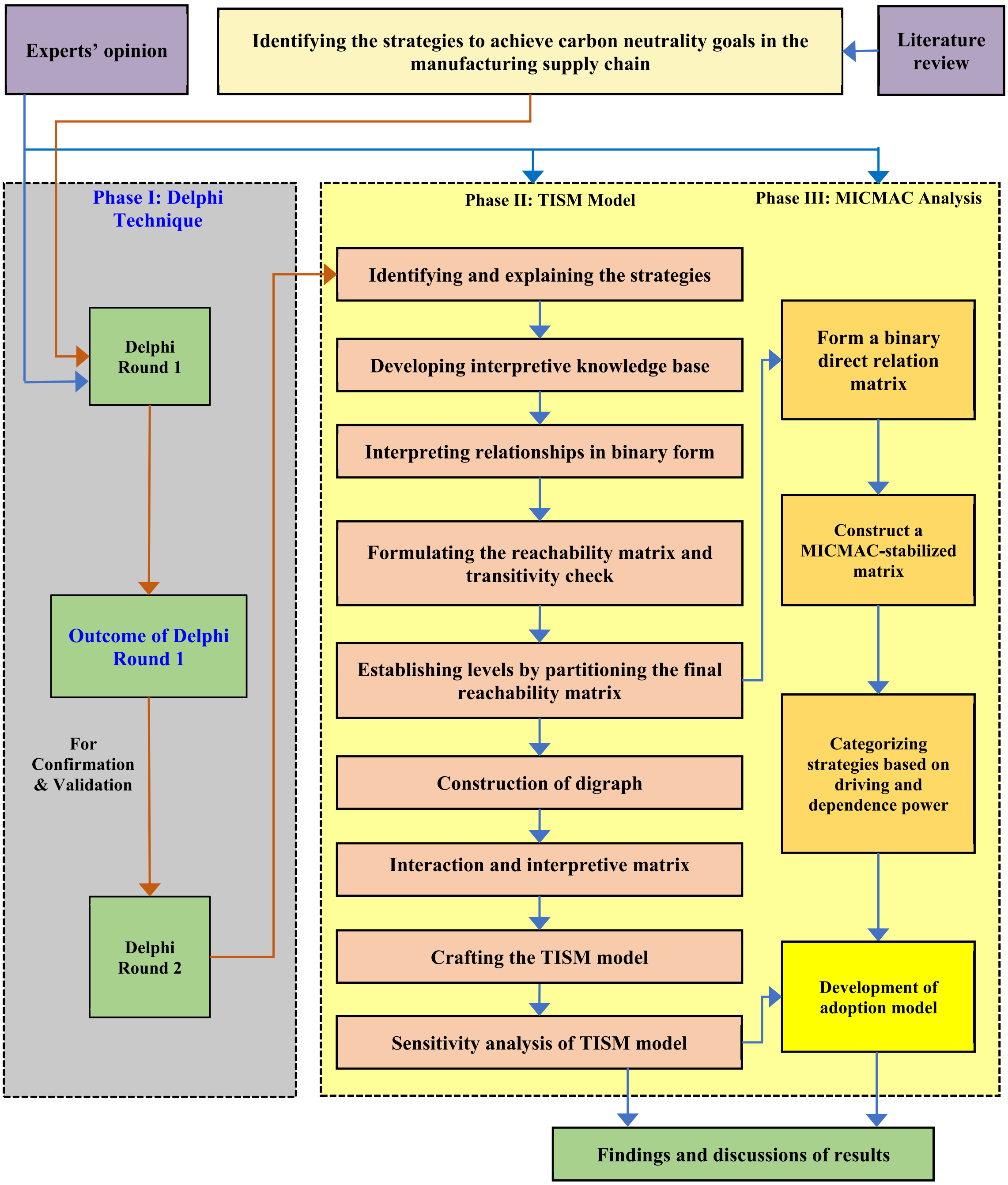

FIGURE 1 | Research process flowchart for the study.

While m-TISM methodology streamlines procedural steps such as checking transitivity simultaneously through a reduced number of pairwise comparisons to enhance modeling efficiency (Sushil 2017). However, the evolving nature of Net-Zero strategies involves complex, non-linear relationships that are not yet fully mapped in existing literature, requiring a more exhaustive, step-by-step interpretive logic to ensure theoretical depth. Thus, the current research intentionally chooses TISM framework. By developing explicit justifications for every transitive link rather than utilizing the procedural efficiency of m-TISM, this study ensures a higher degree of causal transparency for the identified strategies. This rigorous manual validation was deemed essential to provide a robust "why" explanation for the adoption roadmap (Sushil 2012), prioritizing the theoretical depth required for a relatively new area of application over procedural efficiency.

The step-by-step approach of TISM, following Mathivathanan et al. (2022), is explained as follows:

Step 1: Identifying and explaining the strategies

In this step, the strategies finalized from the previous Delphi technique are used to obtain interrelationships among them.

Step 2: Developing an interpretive knowledge base.

During this step, a contextual relationship is defined between the finalized strategies. Experts are questioned individually on

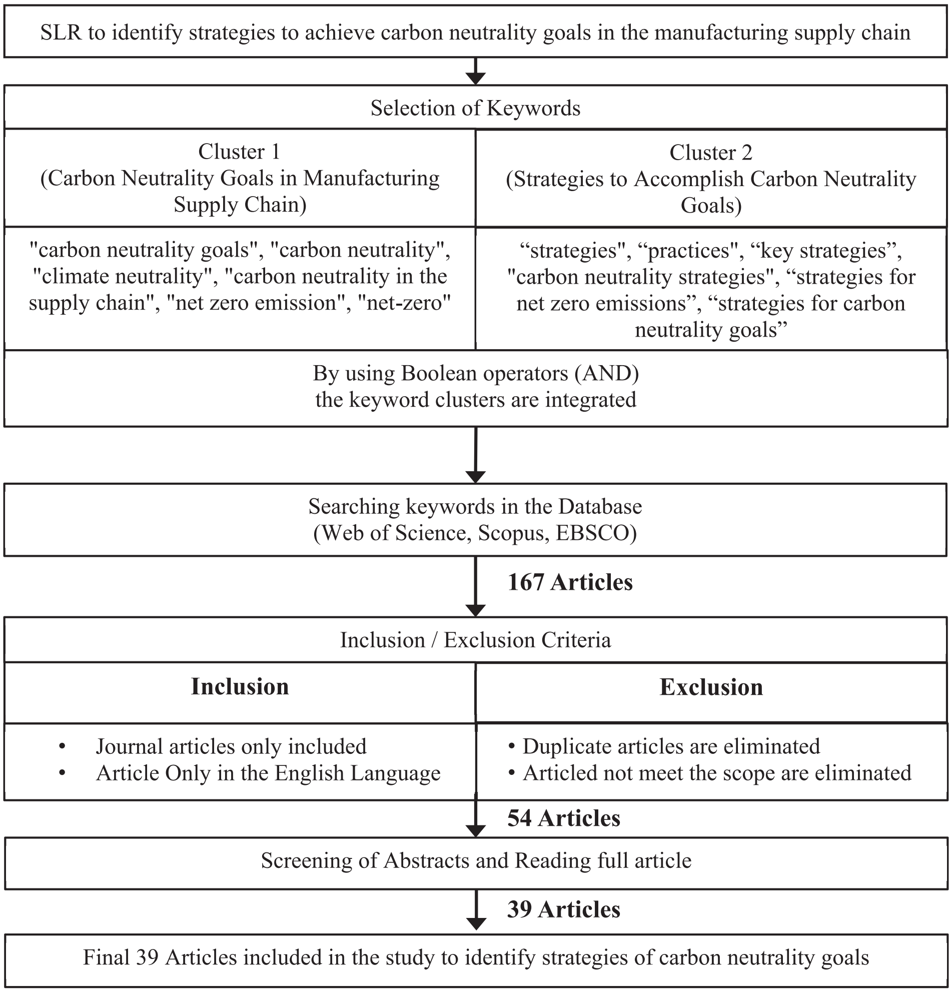

FIGURE 2 | Procedural steps for SLR.

the impact of each strategy over the other. Through brainstorming meetings, the logic behind the influence of one strategy on another is captured. The responses that are validated are utilized to establish an interpretive knowledge domain.

Step 3: Interpreting relationships in binary form to develop the initial reachability matrix.

In the TISM approach, the contextual relationships are established by transforming the "*yes*" or "*no*" in the interpretive knowledge domain to '1' and '0'; this forms the initial reachability matrix.

Step 4: Formulating the final reachability matrix and checking the transitivity.

The transitivity rule is considered while formulating the final reachability matrix, that is, if a strategy "S1" is associated with "S2" and "S2" is associated with "S3", then "S1" is inevitably associated with "S3" (Jayalakshmi and Pramod 2015). Although the transitive relation is determined between strategies, the logic behind the relationships is consulted with experts; it is represented as "1*" in the final reachability matrix. Thus, the interpretive knowledge domain is updated after checking the transitivity (Sushil 2012).

Step 5: Establishing levels by segmenting the final reachability matrix.

In this step, from the final reachability matrix, the reachability set, antecedent set, and interaction set for all strategies are obtained (Warfield 1974). The reachability set comprises the strategy itself and additional strategies that may have influence or effect, whereas the antecedent set is composed of the strategy itself and additional strategies that may be influenced or affected. The intersection set contains strategies identical in both the reachability set and the antecedent set. Level 1 is allocated to a strategy if it is found to be the same in both the reachability set and the antecedent set. In succeeding iterations, these strategies are deleted from the set; this is noted as the closure of iteration 1. The iterations are extended till all strategies are at allocated levels.

Step 6: Crafting the TISM model.

The final reachability matrix information (direct links and significant transitive links) is exhibited in the developed TISM model. The direct relationships among strategies are denoted by a solid line, while a significant transitive relationship between strategies is displayed by a dotted line.

3.3 | Phase III—MICMAC Analysis

The cross-impact matrix-multiplication applied to classification (MICMAC) analysis is utilized to cluster strategies according to the driving and dependence power. This assesses the magnitude of each strategy while considering the relationship's intensity with other strategies (Patel et al. 2021). The degree of influence of one strategy applied to another is driving power; the strategy influenced by others is the dependence power. Thus, a diagram is constructed for driving-dependence power where the dependence power is represented along the x-axis and driving power is shown on the y-axis. The MICMAC analysis categorizes the strategies obtained from the final reachability matrix into four clusters according to the driving and dependence power attained (Sorooshian et al. 2023). These are described as follows:

- *Cluster I (Autonomous):* The first cluster comprises strategies that have weak dependence and driving power.
- *Cluster II (Dependent):* The second cluster comprises strategies that have strong dependence power with weak driving power.
- *Cluster III (Linkage):* The strategies in this cluster have strong dependence and driving power.
- *Cluster IV (Independent):* The final cluster includes strategies with strong driving power and weak dependence power.

3.4 | Sensitivity Analysis

The developed TISM model, according to the interaction matrix, is supposed to validate the relationships among the strategies with the same expert group. Experts are interviewed individually, with all the links depicted in the final TISM model being considered to analyze the logic behind the influential interrelationship of one strategy with another (Sushil 2012; Jayalakshmi and Pramod 2015). The evaluation is performed for every link using a Likert 5-point scale, with "5" being "agreeing strongly" and "1" being "disagreeing strongly". A mean score of 2.5 thus is the mid-point of the scale and provides a rational threshold to separate weak or non-significant relationships (mean < 2.5) from moderate-to-strong relationships (mean ≥ 2.5). The links with a mean score of 2.5 and above are retained; other links are dropped to develop the final TISM model (Rajesh 2017; Singh et al. 2024). Thus, only the effective are presented in the validated TISM model.

3.5 | Integrated Delphi With TISM

The Delphi technique is useful for collecting experts' views when preliminary knowledge to assess the phenomenon is lacking (Garza-Reyes et al. 2019). Moreover, the Delphi technique allows for the accumulation of abundant data in this study, resulting in a better knowledge of the subject matter. It also facilitates access to expert viewpoints from different professional experiences with a credible effort (Prieto-Sandoval et al. 2018). Hence, in this study, TISM is integrated along with the Delphi technique to make insights from experts and model the contextual relationships to identify critical strategies for accomplishing carbon neutrality in supply chains of the manufacturing sector. Incorporating TISM with Delphi augments the statistical credibility of this study as it combines the finest of both these methods to obtain a mixture of qualitative and quantitative assessments. Different methods such as DEMATEL, AHP, ANP, and Structural Equation Modeling (SEM) are available to examine the interrelationships between the elements in addition to TISM. While AHP and ANP are best in assessing the relative weights of the elements, they also need rigorous pairwise comparisons. Compared with ANP and AHP, DEMATEL requires a lot of pairwise comparisons, with experts evaluating the existence, besides measuring the power of the relationship. In such a method, the data acquisition process becomes more difficult. Eventually, in contrast to SEM, TISM acts as an analytical approach mainly utilized in the formation of a conceptual model, while SEM is viewed as a sophisticated statistical technique appropriate for confirming the conceptual models established in advance (Rajan et al. 2021). These considerations result in selecting the TISM method for this study, along with the Delphi technique. Further, MICMAC analysis provides a detailed classification of strategies based on the driving power and dependence power that assist in understanding each strategy's relationships with the others.

3.6 | Data Collection Procedure

The optimal number of expert members should be in the range of six to 12 for a study deploying the Delphi technique (Hasson et al. 2000), particularly if the experts participating have diversified professional experience (Winkler and Moser 2016). In this study, the experts are asked to take part in the Delphi process. The criteria considered for choosing these experts are as follows: academic experts are selected if their expertise domain is closely associated with the areas of carbon neutrality and manufacturing supply chain; experts from industry should have prior work experience in the domain of ESG, decarbonization, and supply chain. The expert panel for this study consisted of 11 experts who have significant academic experience or work experience in net-zero and sustainable supply chains (Table 2). The expert panel here represents a good mix of experienced senior industry practitioners and academics. Including operations managers, ESG/climate neutrality leads, manufacturing executives, and academics who research carbon neutrality, digital supply chains, and sustainable manufacturing.

The group has experience ranging from 6 to 28 years, covering both operational realism and strategic depth. The industry experts offer real-life, operationally relevant insights and experiences in the manufacturing, sustainability transitions, and environmental, social, and governance (ESG) implementation sectors, while the academic subject matter experts contribute theoretically rigorous strategies related to decarbonization, sustainability transitions, and the use of supply chains as research subjects. The combined expertise of the industry and academic experts enhances the credibility and overall robustness of the

TABLE 2 | Experts' details.

Expert no.	Role	Years of experience	Academic qualification	Expertise
E1	Manager—Operations	21	Graduate	Plastic product manufacturing
E2	Manager—ESG Sustainability and CSR	15	Postgraduate	ESG implementation
E3	Senior Manager—Operations	19	Undergraduate	Operations
E4	Manager—ESG and climate neutrality	14	Postgraduate	ESG implementation
E5	General Manager—Manufacturing	28	Undergraduate	Production and operations
E6	Regional Manager – Sales and Marketing	15	Postgraduate	Sustainable sales practices
E7	Professor	22	Doctorate	Carbon neutrality and Supply chain
E8	Professor	21	Doctorate	Digital supply chain
E9	Professor	18	Doctorate	Sustainable Manufacturing
E10	Associate Professor	19	Doctorate	Decarbonization of manufacturing operations
E11	Teaching and Research	6	Doctorate	Climate neutrality

Delphi outcomes through the inclusion of both practitioners' relevance and scholarly validity, which enhances the overall reliability of the TISM and MICMAC analyses.

4 | Results

This section details the deployment of the Delphi and TISM technique to finalize strategies and make further analysis. The outcome of each technique is presented in the following sub-sections.

A thorough SLR is undertaken of relevant peer-reviewed journal articles, industry reports, and policy documents that record a range of strategies on carbon neutrality goals in manufacturing supply chains against the backdrop of searches in peer-reviewed journals and other presented databases, including access to the Web of Science, Scopus, Google Scholar, and EBSCO. The shortened articles are organized using clusters of keywords related to carbon neutrality goals within manufacturing supply chains. The studies identified are then reviewed, allowing us to interpret the definitions, establish how the noted strategies could be achieved, and make sense of the contextual meaning of the strategies proposed by the literature. Some strategies identified have overlapping terms, such as green procurement, eco-design, sustainable sourcing, etc.; these are merged into one category and, in some instances, defined in such a way as to reduce ambiguity from duplication for a broader context and application. This process of screening, reviewing, comparing, and synthesizing enables us to develop an exhaustive list of strategies that encompass both the technological enablers and managerial practices for carbon neutrality; the process removes redundancy and allows for higher-order categories to be reduced to more granular, actionable/practical measures for improving carbon-neutral supply chains, wider than supply chain-specific actions. To deepen the interpretation, the study examines the identified strategies, providing a theoretical foundation to ensure their relevance. Fourteen distinct strategies are finally categorized that can be considered holistically across the operational, organizational, and policy aspects of a carbon-neutral supply chain, as shown in Table 3.

4.1 | Finalization of Strategies Using Delphi

To help assess the strategies, questions are put to experts for their input, such as "Do you consider the strategies of carbon neutrality goals to be pronounced clearly and briefly?" and "Do you believe that any strategies are lacking or excessive? Explain your appropriate answer". The revised strategies to accomplish carbon neutrality goals in the manufacturing supply chain after attaining consensus among experts are presented in Table 4. Strategies are altered to reflect the experts' remarks and recommendations throughout the two rounds. Some strategies are incorporated into a single strategy, whereas the rest are segregated into new strategies to broaden the knowledge base.

In the first round of the Delphi process, the experts' comments on each strategy are initially gathered. Key points are identified to refine the strategies with fresh ideas incorporated according to the experts' suggestions. All the strategies are modified, as presented in Table 4. As demonstrated in Table 4, Strategies 3 ("Carbon offsetting"), 4 ("Carbon tax system"), and 5 ("Carbon pricing mechanism") are combined into a new strategy—("Practicing carbon trading policy"). Similarly, Strategies 6 ("Improve energy efficiency") and 7 ("Green energy technologies") are combined

TABLE 3 | Description of strategies identified from literature.

Initial strategies proposed through the literature	Description	Source
Eliminate negative emission technologies	The impact of environmental taxes has forced the manufacturing industry to adopt green technologies in its supply chain. Manufacturers integrate green technology into their supply chains to enhance product sustainability by reducing carbon emissions while concurrently reducing production costs.	Shen and Li 2019; Bhatia et al. 2024; Huang and Luo 2025
Responsibility and accountability practices	Accounting can augment transparency and accountability while facilitating informed decision-making concerning carbon emissions and initiatives for mitigating climate change. Manufacturers need to be responsible for reducing the impact on society by lowering carbon emissions.	Kaur et al. 2023; Bhatia et al. 2024; Tetteh et al. 2025
Carbon offsetting	The process counterbalances carbon emissions produced by firms or any individual activity by contributing to programs designed to reduce equivalent amounts of carbon emissions to the atmosphere. It assists firms in minimizing carbon footprints substantially and drives them to achieve carbon neutrality goals.	Jiang and Xia 2023; Bhatia et al. 2024; Singh et al. 2025
Carbon tax system	A tax is levied on firms that generate carbon emissions through their processes. Further, the tax system stimulates firms to move towards reducing carbon emissions.	Jiang and Xia 2023; Bhatia et al. 2024; Li, Liang, et al. 2025
Carbon pricing mechanism	It emerges as a strategic approach for regulating carbon emissions, employing a cap-and-trade mechanism that establishes emission limits for entities and allows them to trade permits based on their respective emissions. This system introduces a market for allowances, providing economic incentives for emission reduction and offering flexibility in meeting predetermined targets.	Jiang and Xia 2023; Bhatia et al. 2024; Chen and Guo (2025)
Improve energy efficiency	Investing in renewable energy infrastructure involves building and expanding physical structures for harnessing energy generated from renewable sources like wind, hydro or solar power. These investments are crucial for expanding clean energy capacity, minimizing the dependency on fossil energy, and mitigating environmental impact, ultimately contributing to a more sustainable and resilient energy system.	Hu et al. 2021; Bhatia et al. 2024; Huang and Luo 2025; Wu et al. 2025
Green energy technologies	Firms are investing in technologies that produce alternate sources of energy like solar, wind, etc. Most companies have adopted measures to utilize technologies that produce energy with fewer carbon emissions to move towards carbon neutrality.	Hu et al. 2021; Bhatia et al. 2024; Chen and Guo (2025)
Demonstration and standard formulation	The development and use of renewable energy sources in firms is encouraged by formulating and executing policies by the governments. This can involve providing financial support through subsidies, offering tax incentives to individuals and businesses investing in renewable energy projects, and establishing feed-in tariffs to promote financing in sustainable energy.	Hu et al. 2021; Patil et al. 2024; Huang and Luo 2025
Use of the circular economy	Circular strategies may encourage firms to use the waste materials generated through reuse, recycling, remanufacturing, etc. to minimize the carbon footprint in their supply chain.	Mastos et al. 2020; Patil et al. 2024; Singh et al. 2025
Digitalization	The process of digitalizing operations is aimed at achieving transparency in the supply chain and ensuring effective inventory management. This involves the implementation of digital platforms to facilitate transparency and robust information management.	Patil et al. 2024; Li, Zhu, et al. 2025

(Continues)

TABLE 3 | (Continued)

Initial strategies proposed through the literature	Description	Source
Responsible supplier selection	Supplier selection is crucial in realizing carbon neutrality in the manufacturing supply chain. Supplier selection allows companies to identify and collaborate with suppliers who have effective carbon management systems, training programs, and the ability to provide accurate carbon information. This collaboration can lead to the development of long-term partnerships and the implementation of sustainable practices over the entire supply chain, ultimately contributing to the achievement of carbon neutrality.	Hsu et al. 2013; Sharma et al. 2022; Li, Liang, et al. 2025
Green transportation methods	Efficient heavy goods vehicle (HGV) operations are vital, since they contribute significantly to carbon emissions. To address this, embracing sustainable transportation modes becomes crucial. Green alternatives like electric vehicles (EVs) and hydrogen fuel cells show promise by using renewable energy sources, substantially reducing carbon footprints. Additionally, collaborative routing and reinforcement learning enhance logistics efficiency.	Schoepf et al. 2023; Patil et al. 2024; Tetteh et al. 2025
Efficient internal waste management system	Waste management has been instrumental in attaining carbon neutrality for the manufacturing industry. By optimizing waste management systems, companies can work towards carbon neutrality by addressing all waste fractions sustainably, including recycling, composting, energy recovery, and controlled landfilling.	Fernández-Braña et al. 2020; Bhatia et al. 2024; Huang and Luo 2025
Knowledge sharing	The degree of collaboration and trust has an immediate effect on the visibility of the supply chain, subsequently influencing its sustainability and transparency. Building stronger relationships with supply chain partners can assist in proposing mutual resolution approaches and allows the provision of economic and technical assistance to suppliers.	Hu et al. 2021 Huang and Luo 2025; Tetteh et al. 2025

to form a new strategy—("Renewable energy sources"). The majority of strategies is consistent with the concepts and theory of carbon neutrality and supply chain, in accordance with the views of the experts.

During the second round of the Delphi technique, the experts are again questioned, "Do you believe that this strategy is articulated clearly and curtly and addresses every significant dimension concerning its definition?" Since many of the experts approved the proposed question, only a few modifications are made to the final list of strategies. Thus, based on the experts' suggestions, minor modifications are carried out during the second round to define the following strategies: 1 ("Adoption of green technologies"), 2 ("Adoption of carbon accounting practice"), 4 ("Utilization of renewable energy sources"), 5 ("Policy development and incentive schemes"), 7 ("Digitalization of operations"), 8 ("Partnership with sustainable suppliers"), 9 ("Low carbon emission transportation modes"), and 11 ("Collective and collaborative learning"). Thus, the assertion exhibited in the question is agreed upon by most experts; the Delphi study can thus be concluded after this second round. As presented in Table 4, the final draft consists of 11 strategies to be adopted for carbon neutrality in the manufacturing supply chain; these are analyzed in the TISM approach. The strategies proposed initially for accomplishing carbon neutrality goals are altered based on the experts' input. Final results are presented in Table 4.

4.2 | TISM Analysis

After finalization of the strategies, the brainstorming sessions are conducted with the experts individually to discuss and analyze the relationships between strategies. Considering that this study encompasses a total of 11 strategies, the knowledge base comprehensively covers $11 \times 10 = 110$ potential relationships. For any comparative measure, a positive response requires an affirmative vote from more than 50% of the respondents; otherwise, it is deemed a "*No*". The interpretations provided by our experts are combined (excerpt in Table 5). The comparisons are represented in matrix form, with "*Yes*" replaced with "1" and "*No*" replaced with "0". The constructed matrix, the initial reachability matrix, is shown in Table 6.

The preliminary reachability matrix is examined for possible transitivity by applying the transitivity rule. An instance of one of these transitive relations exists in strategies S1 and S6. By adopting these rules, the final reachability matrix (red colored text indicates transitive links) is developed as shown in Table 7. The identified transitive links are evaluated by the experts and are categorized into significant and insignificant links as presented in Table 8.

From the 23 transitive links recognized, eight are identified as significant links. At the outset, from the final reachability matrix (Table 7), the reachability, antecedent, and intersection set

TABLE 4 | Results of the Delphi technique.

Initial strategies proposed through the literature	Round 1—Delphi		Round 2—Delphi	
	Actions taken	**Results**	**Actions taken**	**Results (strategies used in this study)**
Eliminate negative emissions technologies	Refined	Green Technologies	Refined	Adoption of Green Technologies (S1)
Responsibility and accountability practices	Refined	Carbon Accounting Practice	Refined	Adoption of Carbon Accounting Practice (S2)
Carbon offsetting Carbon tax system Carbon pricing mechanism	Integrated	Practicing Carbon Trading Policy	Retained	Practicing Carbon Trading Policy (S3)
Improve energy efficiency Green energy technologies	Integrated	Renewable Energy Sources	Refined	Utilization of Renewable Energy Sources (S4)
Demonstration and standard formulation	Refined	Policy Development	Refined	Policy Development and Incentive Schemes (S5)
Use of the circular economy	Refined	Circular Strategies	Retained	Circular Strategies (S6)
Digitalization	Refined	Digital Transformation	Refined	Digitalization of Operations (S7)
Responsible supplier selection	Refined	Sustainable Suppliers Selection	Refined	Partnership with Sustainable Suppliers (S8)
Green transportation methods	Refined	Green Transportation	Refined	Low Carbon Emission Transportation Modes (S9)
Efficient internal waste management system	Refined	Efficient Waste Management System	Retained	Efficient Waste Management System (S10)
Knowledge sharing	Refined	Collaborative Learning	Refined	Collective and Collaborative Learning (S11)

are formed. If the strategies present in the reachability set and the antecedent set are identical, then the corresponding strategies will form the intersection set assigned to level 1. Level 1 strategies are then excluded from the complete set for the subsequent iteration. This process is repeated till all strategies are allocated to a level. After dix iterations, all strategies are assigned to their level; the outcomes are shown in Table 9.

Following the previous steps, the initial TISM model is constructed to gain an insight into the interrelationships among the strategies (refer to Figure 3). To construct the TISM model, the direct links and eight significant transitive links shown in Table 8 are considered. Based on the level partitioning, Strategies S1, S6, and S10 at the bottommost level are placed in the TISM model at the uppermost level; Strategy S5 at level six is located at the lowermost level. In a TISM, dashed lines are employed to depict the transitive links that are significant; solid lines are utilized to depict the direct links. Since the bottom–up approach is followed in TISM, the existence of any top-down links is eradicated. Further, the interpretation of these links is developed.

4.3 | Categorization of Strategies Through MICMAC Analysis

Using MICMAC analysis, the classification of strategies is carried out according to the driving and dependence powers calculated from the final reachability matrix (Gadekar et al. 2024). The resulting graphical representation in four quadrants reveals the characteristics of each strategy, as shown in Figure 4. The four quadrants are named autonomous, dependence, driving, and linkage strategies, respectively.

4.4 | Sensitivity Analysis

The TISM model developed (refer to Figure 3) is established from the competence of the expert panel. Since the acquired inputs from the expert team are prejudiced in nature, additional validation is required for the developed model (Karmaker et al. 2021; Vimal et al. 2024). Hence, to evaluate the model, an expert team is established that includes both practitioners from industry and academicians to assess the

TABLE 5 | Interpretive logic knowledge base.

S. No	Notation of strategies under comparison	Paired comparison	Does any relationship exist?	A brief explanation of any if it exists
1	S1–S2	Adoption of green technologies—Adoption of carbon accounting practice	No	_
2	S2–S1	Adoption of carbon accounting practice—Adoption of green technologies	No	_
.	.	.	.	.
.	.	.	.	.
109	S10–S11	Efficient waste management system—Collective and collaborative learning	No	—
110	S11–S10	Collective and collaborative learning—Efficient waste management system	Yes	Collective learning enhances waste reduction.

TABLE 6 | Initial reachability matrix.

Strategies	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
S1	1	0	0	0	0	0	0	0	0	1	0
S2	0	1	1	0	0	1	0	0	0	1	1
S3	0	0	1	0	0	1	1	1	0	0	0
S4	1	0	1	1	0	0	0	0	0	0	0
S5	0	1	1	1	1	0	0	1	1	1	1
S6	0	0	0	0	0	1	0	1	0	1	1
S7	0	1	1	0	0	0	1	1	0	1	1
S8	0	0	0	0	0	0	1	1	0	0	1
S9	0	0	1	0	0	0	0	0	1	0	0
S10	1	0	0	0	0	1	0	0	0	1	0
S11	1	1	0	1	0	1	1	0	1	1	1

interpretations of every link in the developed TISM model. Based on this procedure, of the 39 links (31 direct and 8 transitive), 1 link (between S5—S7) is dropped (Table 10). With the validated 38 links, the final TISM model is drawn up (refer to Figure 5).

While this provides a validated structural view, it is important to recognize that strategies for achieving carbon neutrality are not static. Their relative importance may change depending on external dynamics such as regulatory enforcement, technological advancements, or sudden disruptions in supply chains. These scenario insights are derived from expert deliberations during the validation process, where panel members are asked to reflect on how the relative influence of strategies might change under alternative conditions such as stricter regulations or rapid digital adoption. Together, these steps enhance confidence in the validity and adaptability of the developed framework, making it a practical tool for guiding businesses toward net-zero targets under dynamic conditions.

Building on the validated TISM structure presented in Figure 5 and the driving-dependence analysis from MICMAC, the carbon neutrality adoption model for manufacturing supply chains is developed, as illustrated in Figure 6. This model is the authors' proposed framework, constructed by integrating expert inputs (through the Delphi method) with the hierarchical relationships identified in TISM. The model shows the sequence of strategies to be adopted across levels, along with the corresponding outcomes at each stage. For instance, the adoption process begins with policy and incentive schemes that create clarity and direction for stakeholders. This is followed by carbon accounting practices and collaborative mechanisms, which strengthen knowledge sharing and build the foundation for collective action. Strategies at Level 3

TABLE 7 | Final reachability matrix.

Strategies	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	Driving power
S1	1					1				1		3
S2	1	1	1	1		1	1	1	1	1	1	10
S3			1			1	1	1		1		5
S4	1		1	1		1	1	1		1		7
S5	1	1	1	1	1	1	1	1	1	1	1	11
S6	1					1				1		3
S7	1					1	1	1		1		5
S8							1	1		1		3
S9			1			1	1	1	1			5
S10	1					1				1		3
S11	1	1	1	1		1	1	1	1	1	1	10
Dependence power	8	3	6	4	1	10	8	8	4	10	3	

emphasize digitalization and operational improvements that contribute to emission-free processes, while subsequent levels lead toward comprehensive carbon management. From a broader perspective, strategies spanning Levels 2 through to 6 progressively enhance visibility, stakeholder collaboration, and organizational learning. The process culminates in circular practices at Level 7, which close the loop and reinforce long-term sustainability.

Overall, the adoption model demonstrates not only the stepwise progression of strategies but also the intermediate and final outcomes at each level. At the holistic level, the combined adoption of these strategies strengthens brand image, improves firm performance, and enhances competitiveness relative to peers. Thus, Figure 6 represents a structured, theory-informed, and practice-oriented pathway proposed by the authors to guide manufacturing supply chains toward carbon neutrality.

5 | Discussion of Findings

This study addresses the two RQs stated at the outset. RQ1 concerns the forward-looking strategies that firms must consider as key enablers to attain carbon neutrality in their manufacturing supply chains, while RQ2 asks how these strategies interrelate with one another and can be organized into a structured, forward-looking, action-guiding framework for firms that pursue net-zero ambitions. Using TISM and MICMAC analyses, the study identifies 11 interdependent strategies and classifies them into six levels of hierarchy, illustrating their driving and dependent roles. This allows firms to better determine which initiatives to implement first and how they impact one another.

Policy development and incentive schemes (S5) surface as a key driver strategy at the bottommost level of the hierarchy. In this regard, enforcement of government policies as regulations prompts firms to make considerable changes to their operational environment, whereas incentives decrease the financial barriers that restrict firms from adopting carbon-neutral options (Sindhwani et al. 2022). Adoption of carbon accounting practices (S2) and collective and collaborative learning (S11) are identified as driving strategies since they drive other strategies. Driving strategies act as enablers that transform external pressure into process-based activities, allowing firms to monitor emissions, choose low-carbon transport, and implement green technologies (Rayer et al. 2022; Dohale, Ambilkar, et al. 2024).

The utilization of renewable energy resources (S4) and low carbon emission transportation modes (S9) is also determined as driving and autonomous strategies in the TISM model. S4 and S9 are influenced by S5 and S11 and act as drivers for other strategies, highlighting the interdependence of these initiatives. Government-mandated policies and incentives prompt firms to embrace renewable energy sources and low-emission transportation modes, indicating how external expectations and internal capabilities co-evolve to facilitate carbon-neutral operations (Bhatia et al. 2024; Mohan et al. 2022; Li et al. 2023). Practicing carbon trading policy (S3) is a dependent strategy, with low driving and high dependence powers. While S3 is influenced by S2, S4, S5, and S9, it also influences S6, S7, and S8. Through carbon trading, companies respond to regulatory demands while concurrently configuring their internal processes to account for carbon credits and offsets.

The digitalization of operations (S7) is similarly a dependent strategy that enhances accountability, traceability, and transparency related to carbon management. S7 is directly influenced by S3 and S11 and indirectly influenced by S5, while it in turn influences S10. Digitalization of operations allows companies to reconceive their discrete processes as they interpret stakeholders' expectations, thereby demonstrating how their internal capabilities are reconfigured as a response to external stakeholder pressures (Chang and Chen 2020). Other dependent strategies, including S8, are directly or indirectly determined by strategies S2, S3, and S5, with implications for strategy S6. In this case, supplier engagement encourages collaborative engagement and

TABLE 8 | Transitive link validation.

S. No	Relationships	Derived relationships	Accept/reject link
1	S1–S6	Adoption of Green Technologies—Circular Strategies	Accept
2	S2–S1	Adoption of Carbon Accounting Practice—Adoption of Green Technologies	Accept
3	S2–S4	Adoption of Carbon Accounting Practice—Utilization of Renewable Energy Sources	Reject
4	S2–S7	Adoption of Carbon Accounting Practice—Digitalization of Operations	Reject
5	S2–S8	Adoption of Carbon Accounting Practice—Partnership with Sustainable Suppliers	Accept
6	S2–S9	Adoption of Carbon Accounting Practice—Low Carbon Emission Transportation Modes	Accept
7	S3–S10	Practicing Carbon Trading Policy—Efficient Waste Management System	Reject
8	S4–S6	Utilization of Renewable Energy Sources—Circular Strategies	Reject
9	S4–S7	Utilization of Renewable Energy Sources—Digitalization of Operations	Reject
10	S4–S8	Utilization of Renewable Energy Sources—Partnership with Sustainable Suppliers	Reject
11	S4–S10	Utilization of Renewable Energy Sources—Efficient Waste Management System	Reject
12	S5–S1	Policy Development and Incentive Schemes—Adoption of Green Technologies	Accept
13	S5–S6	Policy Development and Incentive Schemes—Circular Strategies	Accept
14	S5–S7	Policy Development and Incentive Schemes—Digitalization of Operations	Accept
15	S6–S1	Circular Strategies—Adoption of Green Technologies	Reject
16	S7–S1	Digitalization of Operations—Adoption of Green Technologies	Reject
17	S7–S6	Digitalization of Operations—Circular Strategies	Reject
18	S8–S10	Partnership with Sustainable Suppliers—Efficient Waste Management System	Reject
19	S9–S6	Low Carbon Emission Transportation Modes—Circular Strategies	Reject
20	S9–S7	Low Carbon Emission Transportation Modes—Digitalization of Operations	Reject
21	S9–S8	Low Carbon Emission Transportation Modes—Partnership with Sustainable Suppliers	Reject
22	S11–S3	Collective and Collaborative Learning—Practising Carbon Trading Policy	Reject
23	S11–S8	Collective and Collaborative Learning—Partnership with Sustainable Suppliers	Accept

alignment with sustainability objectives across the entire supply chain. S1 is determined directly by strategies S4, S10, and S11, and indirectly by strategies S2 and S5; indeed, our findings also suggest that existing technologies are not sufficient to reach goals set for carbon neutrality and that further investments will be necessary to adopt green technologies (Kumar et al. 2022). Circular strategies (S6), which are influenced by strategies S1, S2, S3, S5, S8, S10, and S11, further exemplify the strategic interdependencies among them when considering the circular economy and carbon reduction in unison (Ivanova and Sanders 2023).

TABLE 9 | Levels of partition of strategies.

Strategies	Reachability set	Antecedent set	Intersection set	Level
S1	1,6,10	1,2,4,5,6,7,10,11	1,6,10	1
S2	1,2,3,4,6,7,8,9,10,11	2,5,11	2,3,6,7,8,11	5
S3	3,6,7,8,10	2,3,4,5,9,11	2,3,7,11	3
S4	1,3,4,6,7,8,10	2,4,5,11	4,6,7,8	4
S5	1,2,3,4,5,6,7,8,9,10,11	5	5	6
S6	1,6,10	1,2,3,4,5,6,7,9,10,11	1,2,4,6,7,8,9,10,11	1
S7	1,6,7,8,10	2,3,4,5,7,8,9,11	2,3,4,6,7,8,9,11	2
S8	7,8,10	2,3,4,5,7,8,9,11	2,4,6,7,8,9,10,11	2
S9	3,6,7,8,9	2,5,9,11	6,7,8,9	4
S10	1,6,10	1,2,3,4,5,6,7,8,10,11	1,6,8,10,11	1
S11	1,2,3,4,6,7,8,9,10,11	2,5,11	2,3,6,7,8,10,11	5

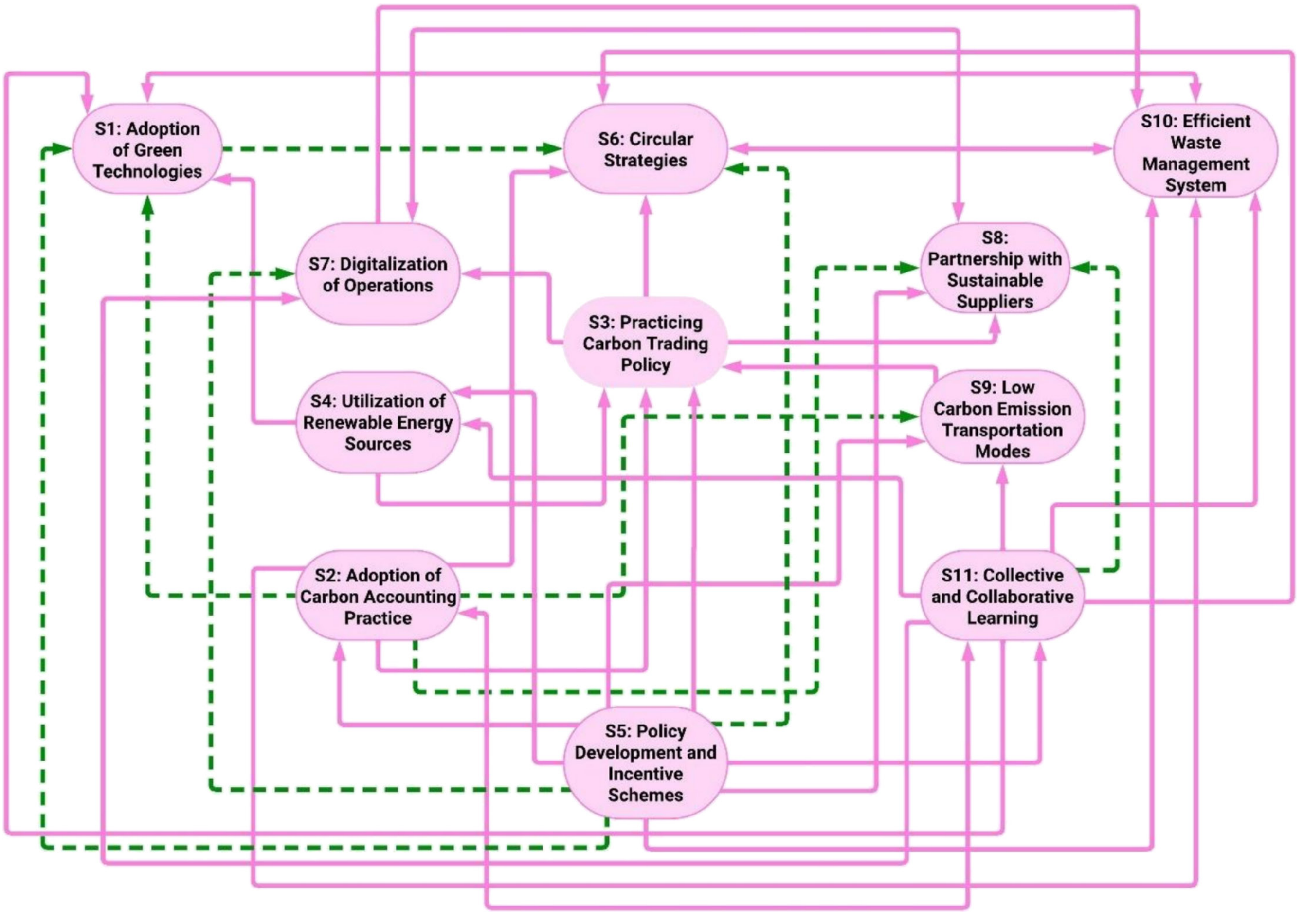

FIGURE 3 | Initial TISM model showing both direct and significant transitive links.

Overall, the findings of this research postulate that carbon neutrality across manufacturing supply chains is underpinned by a synchronous orchestration of strategies at macro (policy, ecosystem, stakeholder expectations) and micro (internal, technological, operational) levels of analysis. The hierarchical nature of the strategies, coupled with the causal linkages among them, provides useful insights as to how a firm should coordinate and implement its various initiatives promptly. By developing a conceptual model that depicts the drivers, the dependencies, and the relationships between these strategies, the study is able to answer both of the research questions (RQ1 and RQ2). Furthermore, based on the findings of this research, Figure 6

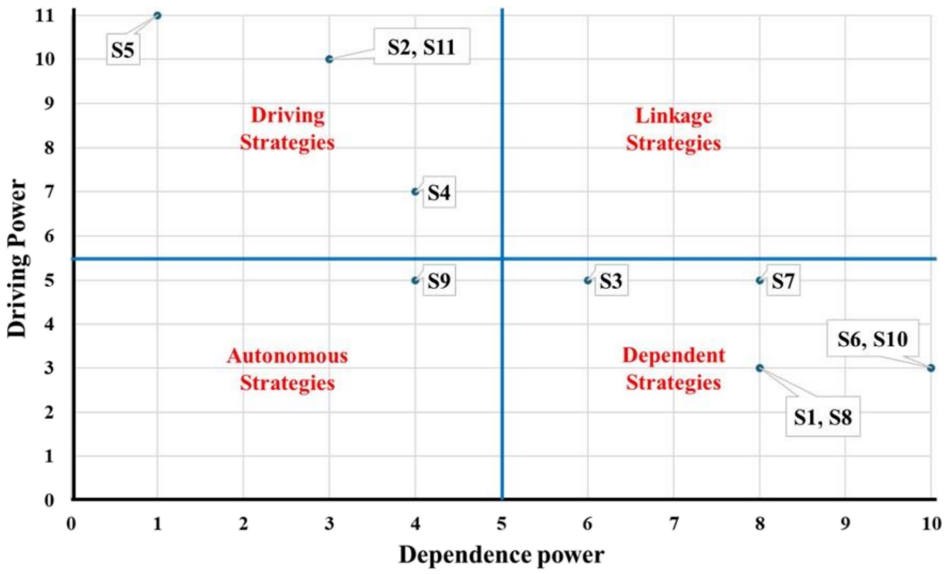

FIGURE 4 | MICMAC categorization.

TABLE 10 | Interpretive matrix.

S. no	Relationship	Interpretation	Experts no. 1	2	3	4	5	6	7	Average score	Accept/ Reject link
I1	S1–S6	Green practices stimulate circular strategies	2	5	5	5	4	3	2	3.71	Accept
I2	S1–S10	Green technologies strengthen waste management practices	4	4	2	3	5	2	3	3.29	Accept
I3	S2–S1	Accounting identifies hotspots, enabling adoption	5	5	4	4	5	4	2	4.14	Accept
I4	S2–S3	Carbon accounting fuels efficient trading	2	3	5	5	4	5	2	3.71	Accept
I5	S2–S6	Carbon accounting fuels circularity	3	3	5	3	3	2	5	3.43	Accept
I6	S2–S8	Transparency strengthens relationships	5	5	3	3	3	2	5	3.71	Accept
I7	S2–S9	Carbon accounting guides low-carbon transport adoption	3	2	4	3	5	3	3	3.29	Accept
I8	S2–S10	Accounting highlights the need for waste reduction	5	3	2	2	4	5	2	3.29	Accept
I9	S2–S11	Carbon accounting fosters collaborative learning	4	3	3	2	3	5	5	3.57	Accept
I10	S3–S6	Carbon markets promote resource recovery from waste	3	2	3	4	2	2	5	3.00	Accept
I11	S3–S7	Trading demand accelerates digitalization	5	2	5	3	2	4	4	3.57	Accept
I12	S3–S8	Carbon trading unlocks green alliances	3	5	2	5	2	5	4	3.71	Accept
I13	S4–S1	Shifting to renewables enables complementary green technologies	5	5	5	4	3	5	4	4.43	Accept
I14	S4–S3	Renewable energy drives carbon trading	3	5	5	4	4	2	2	3.57	Accept

(Continues)

S. no	Relationship	Interpretation	Experts no.							Average score	Accept/ Reject link
			1	2	3	4	5	6	7		
I15	S5–S1	Policies can incentivize green tech adoption	4	3	3	3	3	5	4	3.57	Accept
I16	S5–S2	Policies shape carbon data landscape	2	5	2	3	2	5	4	3.29	Accept
I17	S5–S3	Incentives enhance carbon trading	3	2	4	3	5	2	4	3.29	Accept
I18	S5–S4	Policies accelerate clean energy transition	3	4	5	2	5	5	2	3.71	Accept
I19	S5–S6	Policies cater recovery of wastes	3	3	3	5	4	5	4	3.86	Accept
I20	S5–S7	Policies promote digitalization of operations.	3	2	1	3	1	1	1	1.71	Reject
I21	S5–S8	Policies force sustainable sourcing	3	5	3	4	5	3	5	4.00	Accept
I22	S5–S9	Subsidies promote low-emission transport	4	3	2	4	3	5	5	3.71	Accept
I23	S5–S10	Policies force waste management effectiveness	2	3	2	2	4	4	3	2.86	Accept
I24	S5–S11	Policies foster collaborative learning	3	3	4	3	5	2	4	3.43	Accept
I25	S6–S10	Circularity embraces efficient disposal	3	4	2	5	2	3	4	3.29	Accept
I26	S7–S8	Digitalization enables partnership	2	3	2	3	2	4	2	2.57	Accept
I27	S7–S10	Digital tools optimize resource and increase efficiencies	4	5	5	4	2	2	4	3.71	Accept
I28	S8–S7	Collaboration supports digitalization transformation	5	4	5	3	4	5	2	4.00	Accept
I29	S9–S3	Low-emission initiatives generate tradeable carbon credits	4	5	4	5	4	4	5	4.43	Accept
I30	S10–S1	Waste management enables green technology recovery.	3	2	2	4	4	4	4	3.29	Accept
I31	S10–S6	Waste management systems enable circular adoption	5	3	3	5	4	4	5	4.14	Accept
I32	S11–S1	Collaborative learning fosters green technology adoption	5	2	5	2	2	5	3	3.43	Accept
I33	S11–S2	Collaborative learning fosters the adoption accounting	4	3	4	4	4	3	4	3.71	Accept
I34	S11–S4	Collaboration encourages renewable solutions	3	3	2	3	3	4	3	3.00	Accept
I35	S11–S6	Collaboration drives circular practice adoption	2	5	4	5	3	5	4	4.00	Accept
I36	S11–S7	Collaboration spreads digital use cases	4	5	4	4	4	5	5	4.43	Accept
I37	S11–S8	Learning helps to build relationships	4	5	3	3	5	2	3	3.57	Accept
I38	S11–S9	Collaboration encourages low-carbon methods	2	5	4	2	5	3	4	3.57	Accept
I39	S11–S10	Collaborative learning enhances effective waste management	2	5	2	3	4	4	2	3.14	Accept

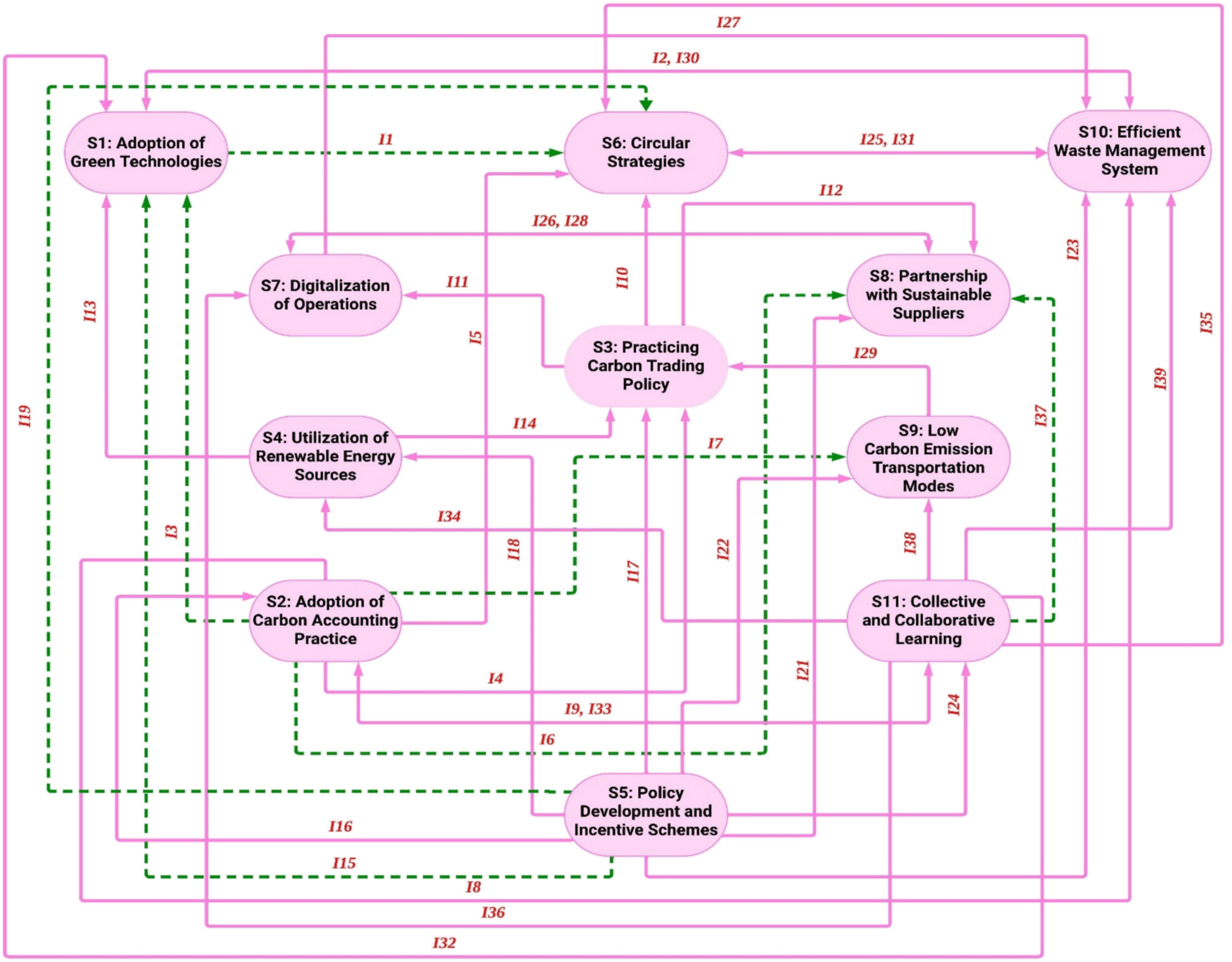

FIGURE 5 | Validated TISM model.

offers a practical adoption model for carbon neutrality in an organization.

6 | Implications

6.1 | Theoretical Implications

The present research contributes in various ways to prior literature on carbon neutrality in manufacturing supply chains. Even though carbon neutrality literature has sufficiently addressed the theoretical progress of drivers, barriers, critical factors, and frameworks for net-zero emissions, identifying the strategies to be adopted within a manufacturing supply chain to accomplish carbon neutrality goals is in its early stages. Through empirical evidence, it depicts the interaction between the strategy and carbon neutrality goals, particularly the internal and external pressures. These pressures force firms to aim for carbon neutrality not only from the perspective of reducing carbon emissions from the industry, but also to enhance the firm's performance and brand image, enabling us to gain better knowledge on the theoretical framework. The findings offer concrete proof that adopting strategies in the supply chain is crucial for attaining carbon neutrality.

The research illustrates the importance of external pressures, including government policies, societal pressure, and market factors, in shaping firms' strategic responses to sustainability. The strategies for S5 emerge as a driving strategy, showing how regulatory mandates cause firms to reconfigure their operations for carbon neutrality, aligned with the study of Majumdar and Sinha (2019). Internal capabilities, such as S2, S7, and S11, illustrate how firms dynamically adapt their resources and processes to respond to these external pressures (Rayer et al. 2022; Chang and Chen 2020). Finally, the interdependencies among strategies, which are uncovered using TISM and MICMAC, provide empirical support for a firm's sustained evolution and reconfiguration of its capabilities associated with pursuing carbon neutrality. Most significantly, this study contributes to theory by presenting a structured adoption model (Figure 6) reconciling driving, linking, and dependent strategies within a single framework. This provides a holistic view to examine the nested nature of interactions required for carbon-neutral operations in manufacturing supply chains. This gives us better insight into strategies for accomplishing carbon neutrality. Also, this study identifies the direct and indirect links (transitivity links) between the strategies by using the TISM approach. The strategies placed at the bottom of the model are more crucial than those strategies placed at the corresponding higher levels. The

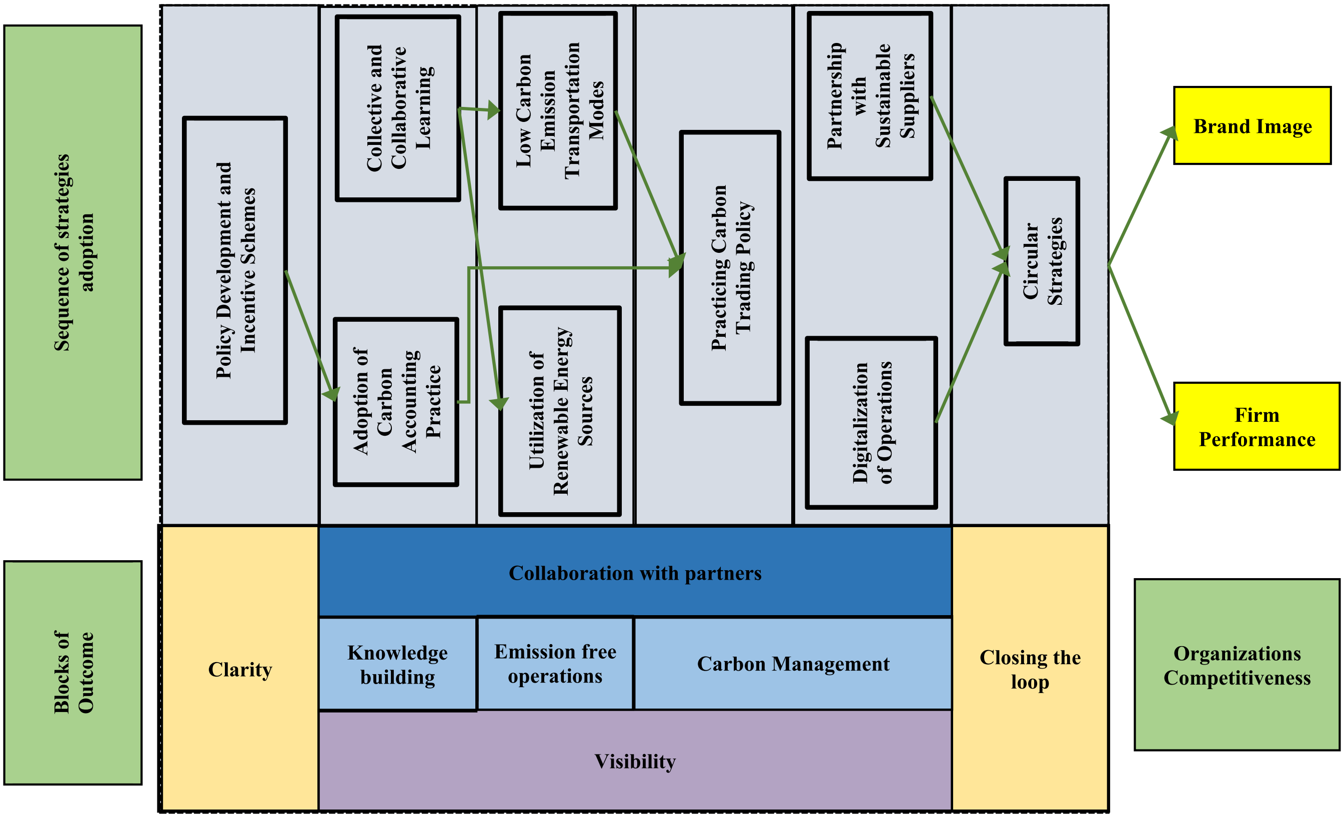

FIGURE 6 | Adoption model for achieving carbon neutrality in manufacturing supply chain.

TABLE 11 | Future research propositions.

Propositions	Implications	Contribution to Net-Zero (NZ)
P1. Stakeholder coordination results in aligned carbon management strategies for manufacturing supply chains.	Highlights the co-creation of sustainability strategies by firms and policymakers (Zhang, Tay, et al. 2023; Bhatia et al. 2024).	Ensures value chain-wide synchronization in emissions management, essential for achieving net zero targets.
P2. Integrating knowledge, sustainable operations, and carbon management enhances competitiveness through compliance, efficiency, and stakeholder trust.	Demonstrates how capability-building and sustainability-focused learning align with market and regulatory demands (Manikandan et al. 2024; Guo et al. 2024).	Promotes organizational readiness and responsiveness, enabling low-carbon transitions that align with net-zero mandates.
P3. A robust policy framework that includes investments in low-emission technologies and incentives that shift the adoption of carbon neutrality into overdrive.	Advocates regulatory clarity and financial support to reduce risk and encourage sustainable investments (Pinkse et al. 2024; Sarpong et al. 2023).	Acts as a catalyst for rapid decarbonization by making green technologies economically viable and scalable.
P4. Collaborative relationships and transparency within the supply chain can help drive circular economy initiatives reducing material waste and enhancing resource efficiency.	Emphasizes shared information systems and joint sustainability efforts (Sharma et al. 2024).	Supports closed-loop systems that cut emissions, optimize resources, and reduce carbon intensity across the chain.
P5. Utilizing a structured adoption model will augment dynamic capabilities through continuous learning, digitalisation, and flexible strategies.	Leverages DCT to enhance firms' ability to adapt and transform operations sustainably (Bhatia et al. 2025; Zheng et al. 2024).	Facilitates smart, data-driven decisions and fosters systemic transformation aligned with net-zero goals.
P6. Achieving carbon neutrality requires a holistic, multi-tiered approach balancing regulation, innovation, and collaboration.	Recognizes carbon neutrality as a systemic transformation requiring aligned action across policy, technology, and firm behaviour (Chen et al. 2022; Liu et al. 2023).	Enables integrated, multi-level decarbonization efforts essential for achieving comprehensive net-zero outcomes.

hierarchical relationship between the strategies is represented by these levels (refer to Figure 4).

6.2 | Managerial Implications

This study provides a well-defined adoption model for managers in manufacturing to achieve carbon neutrality in their supply chains, stressing the importance of connecting both internal capabilities and external pressures. The model for climate adoption provided in this study is one way for companies to establish priorities to put their strategies into action in a systematic way to achieve sustainability. The importance of supply chain emissions is seen in many industrial reports. For instance, the CDP Global Supply Chain Report 2021[10] suggests that the greenhouse gas emissions of an enterprise's supply chain are on average 11.4 times greater than emissions from its direct operations; this is a clear indication that organizations need to manage emissions across their entire supply chain. Similarly, McKinsey's 2023 ESG Report[11] states that, to improve the environmental and social dimensions of the products and services they source, it is vital to bring suppliers into organizational planning.

The results suggest managers should leverage fundamental strategies like commitment to the policies and incentive strategies, which are vital elements of the success of carbon-neutral initiatives. This should be followed up by a concentration on implementing green technologies and circular economy activities while engaging with suppliers to achieve a holistic sustainability approach. Linkage strategies, adoption of carbon accounting practice, and digitalization of operations are also important to drive visibility and inform decision-making across the supply chain. By leveraging the construct-based adoption framework and leveraging internal capabilities to align with external pressures, managers can better navigate the complexity around carbon-neutral solutions in manufacturing supply chains while improving firm performance, competitiveness, and brand image.

In terms of global implications, the overall framework provides a method for companies to operate across various regulatory and institutional environments, while aligning with the world's efforts to combat climate change (i.e., the Paris Agreement). Additionally, the framework helps companies coordinate supply chains across borders, promotes the harmonization of sustainability initiatives throughout regions, and assists multi-national corporations and regulators in implementing large-scale net-zero efforts across their global manufacturing operations.

7 | Conclusions

This study provides a prescriptive and future roadmap that helps manufacturing supply chains to become carbon neutral and therefore contribute to the greater net-zero cause. More importantly, by drawing on literature gaps of the past and the insights of recent years, the study provides a theoretical explanation, where exogenous pressures and endogenous reconfigurations play a critical and complementary role in fostering sustainability transitions. Methodologically, the most significant contribution of this study is in developing a three-stage adoption framework of Delphi, TISM, and MICMAC; although this is not unique, it serves as a powerful tool to systematically surface, structure, and prioritize a set of 11 interrelated strategies. A major novelty here is that, in contrast to previously fragmented adoption patterns, this integrated framework can map the adoption of carbon neutrality at both the firm-level and supply chain-level, and in the process, helps to identify the existence of clear hierarchies and dependencies across these strategies.

With insight, the study shows that carbon-neutral enablers such as policy incentives, carbon trading, digitalization of operations, and adoption of carbon accounting practice act as 'big-push' drivers that speed up the implementation of a set of value-chain level efforts that include, but are not limited to, collaborative learning, waste reduction, and circular economy practices. Furthermore, the proposed framework helps to demonstrate that it is not a single change agent but a set of coordinated actions at both the macro-level (enablers and business ecosystems) and micro-level (firm-level resources and capabilities) that enable carbon neutrality to be achieved. This enriches the theoretical debate where most previous studies focus on either internal factors (capabilities) or external ones (drivers), to show that the two dimensions are not only related, but also significantly interdependent. Practically speaking, this study provides a prescriptive, sequenced pathway that managers and policymakers can leverage to align the firm-level (resources) and ecosystem-level (enablers) efforts towards carbon neutrality in a manner that will build more sustainable, transparent, and resilient supply chains. For policymakers, it can provide evidence-based insights on the nodes in the system where their interventions can have the maximum system-wide leverage. For managers, the study highlights the capabilities and collaborations that are not only necessary to be carbon-neutral, but also need to be competitively prioritized.

Despite its contributions, this study has several limitations. The framework was developed within the context of manufacturing supply chains in emerging economies, which may limit its direct applicability to domains such as agriculture, healthcare, or services. Additionally, the reliance on expert judgment via the Delphi technique introduces a degree of subjectivity. Furthermore, this research focused on 11 key strategies and a targeted group of experts to build a foundational roadmap. Future studies could expand this scope to include a broader set of strategies and a larger, more diverse pool of experts to enhance the generalizability of the findings. In such large-scale modeling, the modified TISM (m-TISM) methodology should be utilized to leverage its increased procedural efficiency while maintaining analytical rigor.

The framework remains at a conceptual level and has not been empirically tested for causality between constructs or its direct impact on organizational performance. To advance this work, empirical testing should be conducted across different industries and geographical regions. Future investigations should also explore the framework's applicability across varying regulations, cultures, and technologies—such as digital twins and AI-enabled analytical tools—to improve predictive validity and tangible feasibility. Overall, this research represents a unique contribution by advancing a structured, theory-based framing for achieving carbon neutrality. By linking firm-level initiatives with the broader global net-zero agenda, these results provide a rigorous stimulus for policymakers and contemporary firms to progress toward sustainable, climate-resilient supply chains.

In addition, this research contributes to the net-zero emission discussion through practical research propositions based on empirical data and theoretical foundations. Our future research propositions provide actionable academic insights by strengthening the net-zero framework through connections between theory and strategy and between strategy and measurable outcomes. These are detailed in Table 11.

Author Contributions

All authors contributed significantly to the work.

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The authors have nothing to report.

Endnotes

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