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DRIVING NET-ZERO AND RESILIENT SUPPLY CHAINS THROUGH INDUSTRY 5.0: A STRATEGIC PATHWAY FOR SUSTAINABLE ECONOMIC DEVELOPMENT

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Abstract. Industry 5.0 (I5.0) based practices help to reduce supply chain emissions while ensuring resiliency. But the evidence on these practices remains limited. Therefore, this study analyses the practices in the context of I5.0 that can enable net-zero and resilient supply chains. We followed a three-phase framework: (1) identify practices through literature review, (2) map their hierarchical relationships using Interpretive Structural Modeling (ISM), (3) evaluate causal influence using the Decision-making trial and evaluation laboratory approach (DEMATEL). The results indicate four important practices: ESG compliance, Life Cycle Assessment (LCA), human-centric and collaborative systems, and mass personalization. These practices help build net-zero and resilient supply chains. From a theoretical perspective, this study bridges the gap between I5.0 theories and the net-zero and supply chain resiliency concept. From a managerial perspective, this study offers a structured pathway to integrate digital and human capabilities for a resilient future. For policymakers, it highlights the need for incentives and infrastructure to improve I5.0 maturity.

Keywords: Industry 5.0, DEMATEL, ISM, net-zero emissions, supply chain resilience, circular economy, human-centric manufacturing, ESG compliance.

JEL Classification: C44, L2, L60, O14.

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1. Introduction

The manufacturing sector at the global level holds a strong place by providing new opportunities for job creation, contributing to the global economy, and meeting the social demands related to goods (Cohen & Zysman, 1987; Taglioni & Winkler, 2016). It also helps to drive innovation, trade, and productivity, which is essential for economic growth (Haraguchi et al., 2017). The manufacturing sector was historically labor-intensive with high reliance on manual work and limited customization (Pereira et al., 2019). Lean practices and just-in-time systems were widely adopted to improve efficiency and reduce waste in manufacturing (Mackelprang & Nair, 2010). Over the last few decades, however, practices have shifted as the market moved from mass production to mass customization (Wang et al., 2017). This transition has been enabled by digital technologies grouped under Industry 4.0. But Industry 4.0 has comparatively less emphasis on human centricity and sustainability (Huang et al., 2022). Therefore, manufacturing is now shifting towards I5.0, which represents a new phase and includes resilience, human centricity, and sustainability as the core pillars (Ghobakhloo et al., 2024).

In the manufacturing sector, the role of the supply chain is important as it ensures the timely delivery of raw materials, which helps in efficient production flow (Schliephake et al., 2009). It also ensures that manufactured goods are transported and distributed to customers, so the supply chain directly impacts the manufacturing cost, quality, and market responsiveness (Jafari et al., 2023). Over the years, supply chain practices have evolved from linear, cost-focused systems to digitally connected and data-driven networks that emphasize resiliency, including flexibility and sustainability (Bechtsis et al., 2021). To enable a digital supply chain, the role of automation, the Internet of Things (IoT), and blockchain technology is important. These technologies help to provide transparency, visibility, and predictive planning across tiers in the supply chain (Hrouga et al., 2022). Traditional supply chain practices include inventory management, demand forecasting, production planning, supplier relationship management, and logistics (Grover et al., 2024). But recent studies discussed advanced practices such as sustainability, risk mitigation, and digital traceability in the supply chain (Rauniyar et al., 2023). In the digital context, these practices require seamless integration across stakeholders. Government and stakeholders now expect improved data security, compliance, and sustainability in the digital supply chain with transparent and inclusive growth (Hong & Xiao, 2024).

In the existing literature, there is substantial discussion about circular and sustainable supply chains. The sustainable supply chain focuses on the balance between economic, environmental, and social goals, while the circular supply chain focuses on reuse, recycling, and closed-loop systems (Genovese et al., 2017; Cataldo et al., 2025). Apart from this, circularity supports sustainability by minimizing waste, reducing carbon footprint, and conserving resources (Xiao, 2025). In this context, circular supply chain resilience refers to the ability of closed-loop systems to maintain performance under disruption by reducing waste, reusing resources, and adapting processes. With this, it also contributes to net zero by extending the product life cycle and minimizing environmental impact through a closed-loop system (Lotfi et al., 2025). Recent literature highlights the need to integrate circular economy principles with digital technologies to build a resilient, low-carbon supply chain (Liu et al., 2023). Existing studies highlight the role of IoT, blockchain, and Artificial Intelligence (AI) to enable traceability, reverse logistics, and sustainable value creation (Mukherjee et al., 2024). Together, these present a unified view that links circularity, resilience, and decarbonization within digitally enabled supply networks.

But key gaps remain in this area due to limited empirical studies on circular supply chain resiliency in emerging economies and a lack of unified metrics to measure the circularity in industries. Moreover, the operational integration of digital tools into circular models remains underexplored, especially on the shop floor and across multi-tier networks. To evaluate progress and compare alternatives, firms also need practical assessment frameworks and indicators that can rank practices by impact and feasibility (Taticchi et al., 2015). In emerging economies, supply chain practices play an important role in improving efficiency, reducing cost, and improving market competitiveness by integrating both digital tools and local sourcing (Akbari & Hopkins, 2022). Apart from this, it also supports resiliency, job creation, and sustainable development. Therefore, assessment of supply chain practices is important and can have a vital impact on the cost reduction and environmental performance (Islam et al., 2018). Particularly, it is important for companies from emerging economies that are expanding their business operations on a global scale. The literature discussed about various decision-making tools for supply chain practices assessment (Taticchi et al., 2015).

Manufacturing supply chain needs to adopt circular economy and net-zero practices to address sustainability issues (Singh et al., 2023). The use of digital technologies and advanced technologies of I5.0 will be helpful to address these issues. However, in a fast-changing technological landscape, adoption of technologies into supply chain practices is not an easy task and thus requires assessment of each practice within its context. Existing studies largely emphasize technological enablers but often overlook human-centric, ethical, and social dimensions. Few studies jointly examine how strategic practices such as corporate social responsibility, Environmental, Social and Governance (ESG) compliance, and management commitment. work with operational technologies (such as simulation, flexible systems, and digital collaboration) to deliver dual outcomes, i.e., resilience and net zero emissions. Also, the causal inter-relationship among these practices is less explored using structural modelling approaches like Interpretive Structural Modeling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL). Also, contextual complexities in emerging economies, including digital maturity, regulatory maturity, Micro Small and Medium Enterprises (MSME) participation, and infrastructure, are less discussed. Existing studies either focused on the environmental consideration or supply chain robustness, with less focus on linkage through a system thinking approach. Without addressing these gaps, the policy and managerial relevance of I5.0 is constrained. To address these issues, this study (i) delineates I5.0-aligned supply-chain practices; (ii) models their causal structure to identify high-leverage drivers and dependencies for resilience and net-zero; and (iii) proposes an assessment approach suited to emerging-economy manufacturing. Therefore, this study is important to assess the supply chain practices with the help of the ISM and DEMATEL approaches.

RQ1: *Which Industry 5.0 aligned supply-chain practices enable circularity, resilience, and net-zero outcomes in emerging-economy manufacturing?*

RQ2: *How do digital technologies (IoT, blockchain, AI) interact with strategic enablers (management commitment, CSR, ESG) to drive these dual outcomes?*

RQ3: *What is the causal structure among these practices, and which are the high-leverage drivers for implementation, as revealed by ISM and DEMATEL?*

To answer the above-stated research questions, we conducted a literature review on supply chain practices in the net zero, resiliency, and sustainability context. The hierarchical structure among the identified practices is determined through the ISM approach. The causal inter-relationship among these practices is investigated through the DEMATEL approach. Further, based on the findings of the study, we proposed managerial and practical insights.

Section 1 discussed the importance of I5.0 for sustainable and resilient supply chains. Section 2 discusses extant studies in the domain. Sections 3 and 4 elaborate on the methods used in this study (ISM and DEMATEL) and the results of these methods, respectively. Discussions are elucidated in Section 5, followed by managerial and theoretical implications in Section 6. Lastly, the paper concludes in Section 7.

2. Literature review

A literature review was conducted using peer-reviewed databases focusing on studies from the last two decades that are aligned with sustainability, circularity, and advanced manufacturing. A total of 16 practices were finalized and subjected to expert review for academic relevance and practical applicability. These practices provide a foundation for modeling and analysis in this study. We searched Web of Science, Google Scholar, and Scopus using search strings: (*"Industry 5.0" OR "human-centric manufacturing" OR "human centric industry"*) *AND* (*"sustainable supply chain" OR "circular supply chain" OR "net-zero supply chain" OR "resilient supply chain"*). The search was limited to articles published in the English language only.

2.1. Supply chain resiliency, circular economy and net zero emissions

A circular economy is a system-level approach that reshapes how products are designed, produced, used, and recovered across the supply chain. It also operationalizes the 6R principles, i.e., reduce, reuse, recycle, redesign, remanufacture, and repair to keep materials and value circulating. Adoption of circular economy practices delivers several supply chain benefits, including improved resource availability and utilization, stronger end-of-life strategies and recovery loops, and improved value proposition through life extension (Lahane et al., 2020). The concept of supply chain resiliency is defined as the adaptive capability of a supply network to anticipate and prepare for disruptions, respond effectively when they occur, and recover in a timely and cost-efficient manner. It aims to restore operations to a stable post-disruption state that meets or improves upon pre-disruption performance through learning and adaptation across processes, resources, and relationships (Tukamuhabwa et al., 2015). There is a strong link between circular economy practices and net zero goals in supply chains under the I5.0 environment. Digitalization and resource optimization are enablers that improve resiliency and reduce emissions at both firm and country levels (Mishra et al., 2023). Chen et al. (2026) link supply chain management to net-zero emissions and discussed a life-cycle view. The study recommended the use of biomaterials, better transport, and electric vehicles to improve sustainability, resiliency, and circular economy goals. The existing literature also suggests that supply chain resiliency can be improved through circular economy strategies like recycling, remanufacturing, and lean manufacturing. These strategies help to lower waste, cost, and energy usage and support sustainability and net-zero goals (Gaustad et al., 2018). Tseng et al. (2020) suggest that circular economy practices improve resiliency through optimal resource usage, waste, and emission reduction. In this context, a multi-level system is needed to track their impact, which helps to achieve net-zero goals and support sustainable growth. Hailemariam and Erdiaw-Kwasie (2023) argue that a shift towards a circular economy is important to reach net-zero emissions targets by 2050. Using data from 29 European countries, it is found that recycling and circular practices reduce CO_2 emissions, strengthen the supply chain, and support sustainability. Chauhan et al. (2023) discussed that integrating supply chain resilience with circular economy practices helps to achieve net-zero goals. Building flexibility and robustness into supply chains improves sustainability and offers a roadmap for strategic improvements. Integrating circular economy principles into sustainable supply chains helps to improve resiliency and reduce emissions. Reusing materials helps to reduce emissions, resource use, and waste (Genovese et al., 2017). Okorie et al. (2023) highlighted that the use of digital technologies and managing intangible assets like labor and supply chain relationships are important to build resilient, net-zero supply chains. Firms can use a resource-based view to support circular economy goals.

2.2. Identification of practices in context of Industry 5.0

To transform supply chains into sustainable and resilient systems, I5.0 integrates advanced technologies, human-centric approaches, and sustainability. Key practices to support this transformation include Corporate Social Responsibility (CSR), promoting ethical commitments to economic, social, and environmental well-being (Rehman & Umar, 2025; Seelent et al., 2025), and management commitment, which support the alignment of leadership and resources to promote sustainability (Castillo et al., 2025). Both CSR and management commitment help to improve the resiliency in the supply chain. In the manufacturing sector, efficiency and sustainable transformation can be achieved through technological integration leveraging AI, IoT, and robotics. These are the I4.0 technologies that support I5.0 outcomes (Hu et al., 2025; Huang et al., 2022). Agility in the supply chain in terms of customization and design changes for sustainable output can be achieved through flexible manufacturing systems (Shukor et al., 2021; Um, 2017). These digital enablers provide the real-time data and control that help to enable simulation, transparency, and life cycle assessment, which improves decision-making. Waste minimization through reuse and recycling strategies helps to achieve resource efficiency and is primarily emphasized by the circular economy (Hadad et al., 2023; Heshmati, 2017). With the help of stakeholder coordination, transparency, and resiliency can be achieved (Gunasekaran et al., 2015; Kazancoglu et al., 2025). Collaboration and information sharing improve transparency and resiliency (Akhavan & Philsoophian, 2023; Baah et al., 2022). Simulation helps manufacturers to enable proactive decision-making (Vlahakis et al., 2020). The adoption of renewable energy in the supply chain helps to reduce emissions in the supply chain (Gawusu et al., 2022). Renewable energy helps to decarbonize the on-site operations, while simulations help in scheduling energy-intensive activities and evaluate trade-offs among cost, service, and emissions to support risk-aware planning. Sustainable manufacturing systems help to minimize environmental impact through eco-efficient technologies (Despeisse & Acerbi, 2022). Life Cycle Assessment (LCA) also plays an important role in evaluating environmental impacts across product life cycles (Sala et al., 2021). Supply chain transparency, which is enabled by digital technologies, ensures the visibility and ethical sourcing (McGrath et al., 2021). ESG compliances help to align operations with the environmental, social, and governance standards for responsible practices (Meiden & Silaban, 2023). The concept of distributed localized manufacturing has become popular in the last few years, which also helps to reduce emissions and improve responsiveness by producing near end users (Rauch et al., 2016; Srai et al., 2016). Human-centric and collaborative systems integrate human skills with technology for inclusive operations (Hammad et al., 2025). Reverse logistics optimizes product returns for resilient networks (Saffari et al., 2023). The mass personalization aspect at the present time helps to deliver customized products in an efficient way to the end users (Wang et al., 2017). These all practices improve responsiveness and recover value from personalized products produced through flexible systems, which improves both material productivity and resilience. The list of I5.0 aligned supply-chain practices that support net-zero and resilient supply chains is summarized in Table 1. These practices were identified through peer-reviewed literature. To verify their relevance and clarity, these practices were discussed with the industry experts discussed in Section 3. These experts were chosen based on purposive sampling. Each of these experts reviewed the definitions. After the validation of these practices, the causal interrelationship among these practices is assessed.

Table 1. Practices to build net zero and resilient supply chains in context of Industry 5.0

P. No.	Practice name	Description	References
P1	Corporate social responsibility	It is a firm’s ethical commitment to support economic, social, and environmental well-being through actions that exceed regulatory compliance	Hsu et al. (2024), Santiago et al. (2025)
P2	Management commitment	It is the proactive involvement of leadership to align goals, resources, and culture to drive sustainability and I5.0 adoption	Castillo et al. (2025), Sonar et al. (2025)
P3	Technological integration and innovation	It involves applying advanced technologies like AI, IoT, and robotics to improve efficiency, agility, and sustainable transformation in supply chains	Ahmed et al. (2023), Sonar et al. (2025)
P4	Flexible manufacturing systems	These are adaptive production systems that enable quick responses to design, volume, or customization changes, improves agility and sustainable output	Dacre et al. (2025), Turner and Oyekan (2023)
P5	Circular economy initiatives	These are the set of strategies and practices that keep materials, products and components in use for as long as possible through reuse, repair, remanufacturing and recycling	Hu et al. (2025), Sonar et al. (2025)
P6	Collaboration and information sharing	It enables seamless coordination and data exchange among supply chain stakeholders, promote transparency, innovation, and operational resilience	Chichi and Mamad (2025), Wu et al. (2024)
P7	Adoption of renewable energy	It involves integrating clean energy sources like solar and wind into operations to reduce emissions, improve energy security, and support sustainability	Azmat et al. (2025)
P8	Simulation	It uses digital models to replicate real-world processes, enable analysis, optimization, and proactive decision-making for resiliency	Chichi and Mamad (2025), Zhu et al. (2025)
P9	Sustainable manufacturing system	These are production frameworks that minimize environmental impact and conserve resources by integrating eco-efficient technologies for long-term resilience	Dossou et al. (2024), Rejeb et al. (2025)
P10	Life cycle assessment	It is a method to evaluate environmental impacts across a product’s entire life cycle	Raman et al. (2025), Turner et al. (2022)

End of Table 1

P. No.	Practice name	Description	References
P11	Distributed localized manufacturing	It enables production near end-users, reduce transport emissions, improve responsiveness, and support local economic development	Leng et al. (2023), Lupi et al. (2023)
P12	Human-centric and collaborative systems	It integrates human skills with advanced technologies to promote safe, inclusive, and efficient environments through improved human-machine collaboration	Grosse et al. (2023), Villar et al. (2023)
P13	Reverse logistics	It focuses on remanufacturing and returning products while using optimization and simulation to build flexible, disruption-resilient supply networks	Dabo and Hosseinian-Far (2023), Fares et al. (2025)
P14	Mass personalization	It enables large-scale production of customized products using advanced technologies, improves customer satisfaction while ensuring efficiency and sustainability	Wang et al. (2024), Wu et al. (2024)
P15	Supply chain transparency	It ensures visibility and traceability across all supply chain tiers, promote accountability, ethical sourcing, and compliance with sustainability standards	Wu et al. (2024), Zhen and Yao (2024)
P16	ESG compliance	It aligns business operations with environmental, social, and governance standards, promotes responsible practices, risk mitigation, and long-term value creation	Asif et al. (2023), Yadav et al. (2025b)

3. Methodology

This study adopts a structured modelling approach to understand and prioritize key supply chain practices that contribute to achieving net zero and resiliency. These identified practices, summarized earlier in Table 1, are used as inputs to the ISM and DEMATEL modelling steps discussed in this section. The practices identified in the context of I5.0 were reviewed and confirmed through a structured consultation with a panel of twelve experts from both industry and academia to combine practical relevance with theoretical rigour and reduce single-perspective bias. The industry experts (supply chain managers, sustainability heads, directors, and policy advisors) were included because these roles own implementation decisions and could judge feasibility in real operations. The academic experts (professors and researchers in smart manufacturing, Industry 4.0 or I5.0, reverse logistics, and decision making) were included to test conceptual clarity and alignment with current research. All the experts were Indian nationals with substantial experience in supply chain and logistics-related roles. Their professional responsibilities covered not only Indian operations but also regional and global supply networks, so the judgments reflect both national and wider international supply chain contexts.

Each expert first reviewed the practice definitions independently to avoid anchoring and groupthink and then provided pairwise comparisons because relative judgement is more reliable than absolute ratings and the same are required to build ISM and DEMATEL models. A moderated discussion reconciled disagreements so that consensus matrices reflected both evidence and experience, with decision logs kept ensuring transparency. The consensus inputs were used in ISM to map the hierarchical structure. The inputs were also obtained for DEMATEL to quantify cause and effect strength. Bias was further mitigated by a common elicitation protocol and mixed panel composition, which helped to improve internal validity, replicability, and industry applicability of the final framework.

3.1. ISM and MICMAC

ISM was proposed by Warfield (1974) and was used to understand and explore the interrelationship among the identified factors or variables. ISM is a highly effective method for tackling complex problems by organizing variables into a clear, hierarchical structure, making it invaluable for strategic planning in areas like supply chain management and sustainability. It excels at simplifying intricate systems by identifying dependencies and prioritizing critical factors based on expert insights, particularly when quantitative data is scarce or subjective. The pairwise matrix developed with the inputs of the experts was used to develop the Structural Self-Interaction Matrix (SSIM), which was later converted into a binary reachability matrix. To ensure logical consistency, the transitivity rule was employed. It resulted in the Final Reachability Matrix (FRM). Further level portioning was used to identify levels of practices based on their reachability and dependence sets. MICMAC analysis was carried out using the obtained driving and dependence power. The analysis helps to classify the practices into four categories, i.e., autonomous, dependent, linkage, and driving. Integration of MICMAC with ISM helps to understand not only the structured influence hierarchy but also their influence and dependence strength.

While both MICMAC and DEMATEL analyze interrelationships among practices, they answer different questions. MICMAC uses the reachability matrix obtained from ISM to classify practices into driver, dependent, linkage, and autonomous groups based on their driving and dependence power. Whereas DEMATEL works with a normalized direct relation matrix and calculates prominence and relation values to form cause and effect groups. Therefore, in this study, MICMAC explains the structural role of each practice in the hierarchy, whereas DEMATEL quantifies the net causal influence.

3.2. DEMATEL

To study the causal relationship among the identified practices, the technique called DEMATEL appears to be most suitable (Si et al., 2018). This method is particularly valuable in scenarios with uncertainty, such as designing resilient supply chains or integrating advanced technologies, as it leverages expert knowledge to handle both qualitative and quantitative data. By clarifying interdependencies, DEMATEL supports strategic decision-making, ensuring that interventions target the most impactful elements, making it indispensable for navigating interconnected challenges in rapidly evolving industries. To deploy the technique, the expert panel was approached and was asked to provide their responses using a 0–4 scale. The obtained inputs were aggregated to build a direct relation matrix, which was then normalized and converted into a total relation matrix to understand the influences. Later sums and differences of influences were obtained as D+R and D-R values for each practice. These values suggest the cause-and-effect nature of the practice.

The triangulation of ISM, MICMAC, and DEMATEL provided a robust multi-perspective understanding of how I5.0 practices interact and contribute to achieving a sustainable, resilient supply chain. The DEMATEL approach follows the steps discussed (Dalvi-Esfahani et al., 2019a; Travisco et al., 2023; Cheng et al., 2024; Liang et al., 2025).

Step 1: In step 1, opinions from experts involved in the study were gathered. Let us consider that there are n experts $E = E_1, E_2, \ldots, E_n$ who rate the influence of practices $P = \left\{P_1, P_2, \ldots, P_z\right\}$. Here, z represents the total number of practices used in this study. The k^{th} expert provides a direct influence matrix that shows how each practice influences the others $X_k = \left[x_{ij}^k\right]_{z\times z}$. x_{ij}^k shows the expert E_k view on how much practice P_i influences practice P_j. A higher value means a stronger influence of P_i on P_j.

Step 2: Computation of average matrix X.

The average matrix $X = \left[X_{ij}\right]_{z\times z}$ combines the views of all n experts as follows:

$$x_{ij} = \frac{1}{n}\sum_{k=1}^{n} x_{ij}^k, \ \ i, j = 1, 2, \ldots, z. \tag{1}$$

Step 3: After calculating the average matrix X, the normalized influence matrix $A = \left[a_{ij}\right]_{z\times z}$ is obtained as:

$$A = \frac{X}{s}, \tag{2}$$

where s = max(X_{ij}) is the largest value in the average matrix X, used to normalize all influence scores into the [0,1] range.

Step 4: In this step total influence matrix is calculated. Experts only provided their judgments on how directly one practice affects another. The total influence matrix T is calculated as follows:

$$T = A + A^2 + \ldots + A^h = A\left(I - A\right)^{-1}, \tag{3}$$

where T is the total influence matrix, where each element t_{ij} shows both the direct and indirect influence of practice P_i on practice $P_{j,}$ and h is selected such that adding further powers of A does not significantly change the matrix values.

Step 5: In this step, vector D and R are calculated to obtain the influence relation map as follows:

$$D = \left[d_i\right]_{z\times 1} = \left(\sum_{j=1}^{z} t_{ij}\right)_{z\times 1} \quad ; \tag{4}$$

$$R = \left[r_j\right]_{1\times z} = \left(\sum_{i=1}^{z} t_{ij}\right)_{1\times z} \quad , \tag{5}$$

where D represents driving power, i.e., total influence given by each practice, and R represents dependence power, i.e., total influence received by each practice. d_i is the sum of the i^{th} row of matrix T, showing how much influence practice P_i has on others. Similarly, r_j is the sum of the j^{th} column of T shows how much influence practice P_j receives from others. The roles of practices are shown using a graph with axes (D+R) and (D−R). Where, (D+R) shows how important a practice is overall, and (D−R) shows if it mainly influences others or is influenced. If (D−R) is positive, the practice is a driver (it affects others). If (D−R) is negative, the practice is a receiver (it is affected by others).

The influence-relation map diagram is constructed by plotting values (D+R, D−R), offering clear insights for decision-making. To simplify the diagram, a threshold is set. Only factors with influence values above the threshold in matrix *T* are used to form the final influence-relation map.

4. Results and analysis

4.1. Interpretive structural modelling

Interpretive Structural Modelling (ISM) is applied to assess the possible interrelationship between different I5.0 practices for Net Zero and resilient supply chain (Ahmad & Qahmash, 2021). The method integrates theoretical, conceptual, and computational analysis of the data (Akhouri et al., 2024). It is an advanced decision-making technique to represent the mutual interaction among the variables (Luthra et al., 2020; Caboz et al., 2025; Yang et al., 2024).

The structural self-interaction matrix is shown in Table 2, where 'O' represents that there is no relationship between the variable *i* and *j*, ‘X’ shows that there exists a both direction relationship between *i* and *j* (both influence each other), ‘V’ represents that there exists a direct relationship from variable *i* to *j* and ‘A’ represents that there exists a relationship in the opposite direction (from *j* to *i*). The results of the self-interaction matrix are further analyzed by converting it into a final reachability matrix, as shown in Table 3.

The reachability matrix is developed by adjusting the initial matrix according to the researcher’s inference. The variables with no relationship are assigned a value of zero, and matrix value one is assigned to the variables having either direct or reciprocal influences on each other. The final matrix is further utilized to classify the practices on the basis of driving power and dependence power of the practices. In other words, the matrix helps identify the reachability set and the antecedent set. The reachability set includes the practice itself and other practices that it can directly or indirectly influence. The antecedent set includes practice itself and other practices that can directly or indirectly influence it. The overlap of practices in both reachability and antecedent sets is considered the intersection set.

Table 2 shows the Structural Self-Interaction Matrix (SSIM). It is used to assess the relationship between the identified supply chain practices. Table 2 illustrates the relationship among the practices and the directional influences based on the expert’s perceptions. Corporate social responsibility (P1) and management commitment (P2) show consistent high-level influence, which reflects the strategic intent and leadership engagement as the backbone of subsequent sustainability-oriented actions. This drives technological integration and innovation (P3), flexible manufacturing systems (P4), circular economy initiatives (P5), and collaboration and information sharing (P6). Technological integration (P3) demonstrates a strong relationship with nearly all subsequent practices, thereby strengthen simulation (P8), sustainable manufacturing systems (P9), life cycle assessment (P10), distributed localized manufacturing (P11), human-centric and collaborative systems (P12), reverse logistics (P13), mass personalization (P14), and supply chain transparency (P15). Influential pattern shows how flexible manufacturing (P4) supports circular economy initiatives (P5), renewable energy

Table 2. Structural Self-Interaction Matrix (SSIM)

Practices	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
P1	–	O	X	V	O	V	O	V	O	V	O	V	O	V	V	V
P2	–	–	V	V	O	V	O	V	O	V	O	V	O	V	V	V
P3	–	–	–	V	O	V	O	V	O	V	O	V	O	V	V	V
P4	–	–	–	–	O	X	O	X	V	V	O	V	O	V	V	V
P5	–	–	–	–	–	O	X	O	X	V	V	V	V	V	O	V
P6	–	–	–	–	–	–	O	X	O	V	O	V	O	V	O	V
P7	–	–	–	–	–	–	–	O	X	V	V	V	V	V	O	V
P8	–	–	–	–	–	–	–	–	V	V	O	V	O	V	O	V
P9	–	–	–	–	–	–	–	–	–	X	V	V	V	V	O	V
P10	–	–	–	–	–	–	–	–	–	–	V	V	V	V	O	V
P11	–	–	–	–	–	–	–	–	–	–	–	V	X	V	X	V
P12	–	–	–	–	–	–	–	–	–	–	–	–	O	X	O	X
P13	–	–	–	–	–	–	–	–	–	–	–	–	–	V	X	V
P14	–	–	–	–	–	–	–	–	–	–	–	–	–	–	O	X
P15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	V
P16	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

adoption (P7), and other downstream systems by offering operational adaptability that enables recycling, remanufacturing, and clean energy integration. Circular economy initiatives (P5), collaboration (P6), renewable energy adoption (P7), and sustainable manufacturing (P9) influence each other through linkages. Downstream practices such as reverse logistics (P13), mass personalization (P14), supply chain transparency (P15), and ESG compliance (P16) reflect incoming influences from technological and organizational practices.

It also signifies that corporate social responsibility (P1), management commitment (P2), and technological integration and innovation (P3) practices play an important role in building supply chain resilience and developing a net-zero economy. The reachability matrix converts the SSIM results into binary values to facilitate the understanding of the indirect links and the levels of the practices. The reachability matrix shown in Table 3 helps to quantify the influence between the practices. It presents the hierarchical structure among the practices and identifies the dependent and driving practices in the hierarchy.

The final reachability matrix shown in Table 3 highlights the direct and transitive influences among the identified practices. Each '1' indicates that the practice in the corresponding row influences the practice shown in the column. '*' indicates the transitive relationship between the practices. The driving power score highlights the number of practices that are influenced by that practice. Whereas the score of dependence power indicates the number of practices that influence that given practice. The results show that corporate social responsibility (P1), management commitment (P2), and technological integration and innovation (P3) have the highest driving power and influence ESG compliance (P16) practices. This indicates that they are the key enablers within the system. The score of dependence power indicates that human-centric and collaborative systems (P12), mass personalization (P14), and ESG compliance (P16) are highly dependent on other factors and have high dependence scores and low driving scores. The practices P4 to P10 show moderate driving and dependence power, indicating their role as the transitional practices that are both influenced and influencing practices. The reachability matrix forms a quantitative base for level partitioning and model structuring in ISM.

Level partitioning shown in Table 4 is applied to classify the practices into a hierarchy or levels on the basis of reachability and antecedent sets. The practices at a higher-level influence other practices, whereas practices at the lower level are more dependent on others. The outcomes of level partitioning are shown in Table 3. The highest level is six, and the lowest level is one. Level one shows that practices that are influenced by higher-level practices have limited influence on others. Practices included in level one are human-centric and collaborative systems (P12), mass personalization (P14), and ESG compliance (P16).

The practices included in the second level are distributed localized manufacturing (P11), reverse logistics (P13), and supply chain transparency (P15). These practices are driven by most of the higher-level practices but have a limited influence on those practices.

Similarly, level three includes circular economy initiatives (P5), adoption of renewable energy (P7), sustainable manufacturing systems (P9), and life cycle assessment (P10). These practices are the bridge between the practices in level one and level four. The practice in this level reflects the two-way influence on the practices in the upper and lower levels. The practices in level 4 include P4, P6, and P8. These practices are dependent on top-tier practices. Level 5 includes practices like corporate social responsibility (P1) and technological integration and innovation (P3). These practices with the level 4 practices, are strategic drivers that convert high-level strategy into actionable directives. Level 5 practices are only dependent on each other has have limited antecedent dependence. Level 6 includes management commitment (P2). It is the primary driver that initiates change, but it is not driven by other practices. The practices at levels 5 and 6 are the practices at the highest level, and they are the most influential practices. These practices have high driving power and are considered the most significant practices in the adoption of I5.0 practices in supply chain management. Corporate social responsibility (P1), management commitment (P2), and technological integration and innovation (P3) practices are considered the most important drivers and need to be more focused for the effective implementation of I5.0.

The driving practices and dependent practices are graphically presented in Figure 1. The digraph is used to visually reflect the direct links between the practices. The digraph is developed from the final reachability matrix and the final level partition matrix. The digraph shows that there are no autonomous practices; in other words, all the 16 practices identified in the study are interrelated. The practices with high dependence power and weak driving power show that they have a limited impact on the other practices. However, they are sensitive to the change in other practices. Whereas the factors with high driving factors and weak dependence factors show that there is a strong influence of these factors on the other variables, and are not significantly impacted by them. Corporate social responsibility (P1), management commitment (P2), and technological integration and innovation (P3) are located at the furthest left and highest, confirming them as the principal drivers. Flexible manufacturing systems (P4), collaboration and information sharing (P6), and simulation (P8), which belong to level 4, are in the driving quadrant and indicate that they translate the level 6 intent to the actions in the system.

Table 3. Final Reachability Matrix (FRM)

Practices	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	Driving power
P1	1	0	1	1	1*	1	1*	1	1*	1	1*	1	1*	1	1	1	15
P2	1*	1	1	1	1*	1	1*	1	1*	1	1*	1	1*	1	1	1	16
P3	1	0	1	1	1*	1	1*	1	1*	1	1*	1	1*	1	1	1	15
P4	0	0	0	1	1*	1	1*	1	1	1	1*	1	1*	1	1	1	13
P5	0	0	0	0	1	0	1	0	1	1	1	1	1	1	1*	1	10
P6	0	0	0	1	1*	1	1*	1	1*	1	1*	1	1*	1	1*	1	13
P7	0	0	0	0	1	0	1	0	1	1	1	1	1	1	1*	1	10
P8	0	0	0	1	1*	1	1*	1	1	1	1*	1	1*	1	1*	1	13
P9	0	0	0	0	1	0	1	0	1	1	1	1	1	1	1*	1	10
P10	0	0	0	0	1*	0	1*	0	1	1	1	1	1	1	1*	1	10
P11	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	6
P12	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	3
P13	0	0	0	0	0	0	0	0	0	0	1	1*	1	1	1	1	6
P14	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	3
P15	0	0	0	0	0	0	0	0	0	0	1	1*	1	1*	1	1	6
P16	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	3
Dependence power	3	1	3	6	10	6	10	6	10	10	13	16	13	16	13	16	

Table 4. Level Partitioning (LP)

Elements (Mi)	Reachability set R(Mi)	Antecedent set A(Ni)	Intersection set R(Mi)∩A(Ni)	Level
1	1, 3,	1, 2, 3,	1, 3,	5
2	2,	2,	2,	6
3	1, 3,	1, 2, 3,	1, 3,	5
4	4, 6, 8,	1, 2, 3, 4, 6, 8,	4, 6, 8,	4
5	5, 7, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	5, 7, 9, 10,	3
6	4, 6, 8,	1, 2, 3, 4, 6, 8,	4, 6, 8,	4
7	5, 7, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	5, 7, 9, 10,	3
8	4, 6, 8,	1, 2, 3, 4, 6, 8,	4, 6, 8,	4
9	5, 7, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	5, 7, 9, 10,	3
10	5, 7, 9, 10,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10,	5, 7, 9, 10,	3
11	11, 13, 15,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 15,	11, 13, 15,	2
12	12, 14, 16,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,	12, 14, 16,	1
13	11, 13, 15,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 15,	11, 13, 15,	2
14	12, 14, 16,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,	12, 14, 16,	1
15	11, 13, 15,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 15,	11, 13, 15,	2
16	12, 14, 16,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,	12, 14, 16,	1

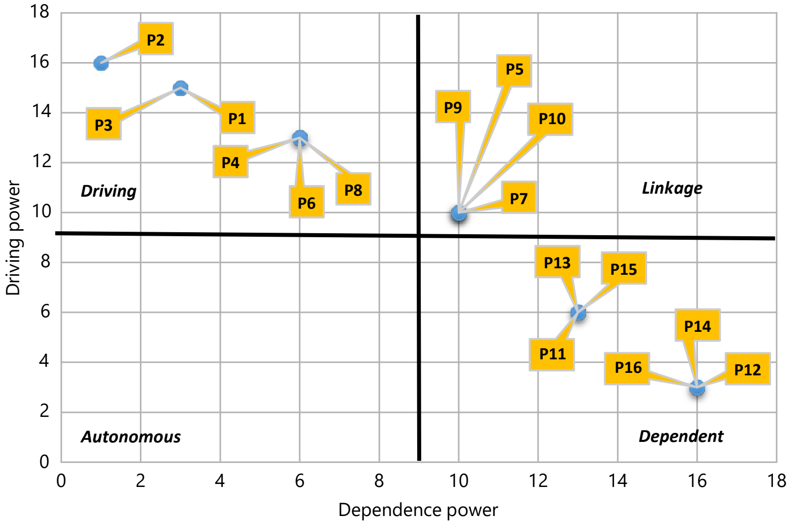

Figure 1. MICMAC classification of practices

Level 3 practices, circular economy initiatives (P5), adoption of renewable energy (P7), sustainable manufacturing systems (P9), and life cycle assessment (P10) are located in the linkage region and have high driving as well as dependence power, and have capabilities to change the entire system. Therefore, it is highly suggested that they need careful attention and consideration.

The practices in the dependent quadrant are distributed localized manufacturing (P11), reverse logistics (P13), supply chain transparency (P15) from level 2, and human-centric and collaborative systems (P12), mass personalization (P14), ESG compliance (P16) from level 1. These practices have high dependence power, indicating that their performance is influenced by higher-level practices. They are considered the outcome or evaluation practices. The influence of the practices in each level is represented in Figure 2, which shows the ISM digraph obtained from the level partitioning shown in Table 4.

The practices with high driving power have a considerable influence on the other supply chain practices of I5.0 to address supply chain resilience and circular economy issues. ISM is applied to categorize the supply chain practices into six levels according to their importance and driving power, as shown in Figure 2. The results show that prioritizing the practices can ensure the successful building of a resilient supply chain and the adoption of circular economy practices. The practices of high importance include corporate social responsibility (P1), management commitment (P2), and technological integration and innovation (P3) practices, included in levels 6 and 5. The arrow depicts the direction of influence of the practices. Figure 2 shows the practices in each level identified from the level partitioning results. The level 6 drives the practices immediately above it. The ISM digraph provides a stepwise roadmap for the decision makers. Level 1 practices capture the strategic outcomes dependent on other practices of a higher level 2, which includes intermediate outputs that are possible through the adoption of the strategic plan of practices of higher levels.

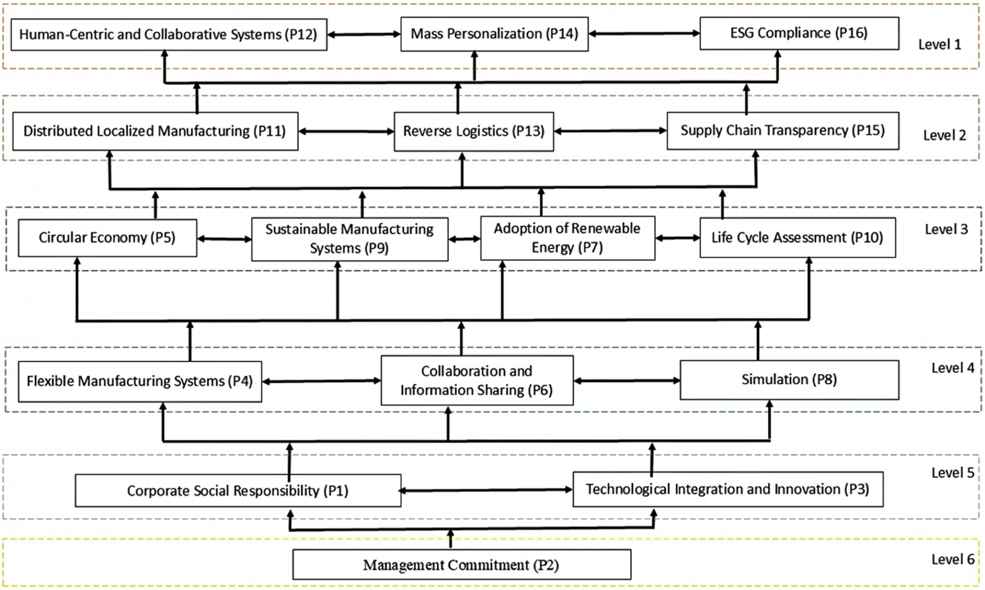

Figure 2. ISM Diagraph

The results recommend that in order to successfully adopt I5.0 supply chain practices to build a resilient circular economy, the focus should be on the practices of a higher level. Further to understand the in-depth causal relationship of the practices and to validate the relationship established through ISM-MICMAC analysis, another Multi-Criteria Decision-Making (MCDM) method, DEMATEL, is applied to quantify and identify the inter-relationship between the practices. DEMATEL can analyze complex systems and visualize cause-and-effect relationships between different factors, making it a powerful tool for various decision-making scenarios._

4.2. DEMATEL

We applied the DEMATEL approach to classify practices into causal and effect groups. The objective was also to quantify their interdependencies and assess how strongly one practice influences another. The expert responses are recorded in a direct relation matrix. The matrix represents the direct influence of each practice on others. The value of the influence ranges from 0 to a higher number; zero indicates there is no influence, and a higher number indicates a stronger influence. The matrix is then normalized to eliminate data redundancies. Table 5 shows the input matrix. Table 6 indicates the total and net effect of all the practices. D+R signifies the total influence potential and importance of each practice. Whereas D-R indicates the net influence of each practice. The causal inter-relationship diagram is shown in Figure 3.

Table 5. Input matrix for DEMATEL

Input matrix																
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
P1	0	2	1.33	1.33	2.33	2.33	2.33	3.33	1.67	2	2.33	2.33	2.33	3.33	1.67	2
P2	1.33	0	2.33	1.67	2.67	1.67	2.33	3.67	4.33	4.33	1.67	2.33	3.67	4.33	4.33	4.33
P3	2.33	2.33	0	2.33	2.33	1.67	2.67	3.67	4.67	4.67	1.67	2.67	3.67	4.67	4.67	4.67
P4	3.67	1	2.33	0	2.33	3	2.33	2.33	1.33	4.33	2	2.67	2	3.67	2.33	4.33
P5	1	1.33	3	2.33	0	2.67	2.33	1	2.33	1.33	2.33	3	2.33	2.33	1.33	4.33
P6	1.33	3.33	1.33	2.67	2.33	0	2.33	3.67	2.67	2.67	1.33	2	1.67	1.67	2.33	2.67
P7	1.33	2	1.67	1.67	2.33	2.33	0	3.67	2.67	2.67	2.33	1.67	2.67	1.67	2.33	2.67
P8	2	2.67	2	3.67	2.33	2.33	2.33	0	2.33	3.33	1.67	2.67	1.33	2.33	2.33	3.33
P9	1.67	2.67	1.33	2.33	2.33	2.67	2.33	3.67	0	3.33	2	2.67	2	3.67	2.33	3.33
P10	3.67	1.67	2.67	2.33	2.67	3.33	3.67	3.67	3.67	0	2.33	3	2.33	2.33	1.33	4.33
P11	2.33	1.67	2.67	1.67	2.33	3.67	4.33	4.33	1.67	2.33	0	4.33	4.33	4.33	3.67	4.33
P12	2.33	1.67	2.67	1.67	2.33	3.67	4.33	4.33	1.67	2.33	3	0	2.33	1.33	4.33	4.67
P13	1.33	2	1.67	1.67	2.33	2.33	1.33	2	1.67	1.67	2.33	2.33	0	3.33	3.67	4.33
P14	2	2.67	2	3.67	2.33	2.33	2.33	2	2.67	2	3.67	2.33	2.33	0	2.33	1.33
P15	1.67	2.67	1.33	2.33	2.33	2.67	2.33	3.67	1.67	2.67	1.33	2.33	2.33	2.67	0	3.67
P16	3.67	1.67	2.67	2.33	2.67	3.33	3.67	3.67	3.67	2.33	2.33	2.67	2.33	3.67	3.67	0

Table 6. Final matrix with net effect and rank

	D	R	D+R	D–R	Rank
P1	3.35	3.33	6.68	0.03	16
P2	4.59	3.28	7.87	1.31	10
P3	4.94	3.22	8.17	1.72	7
P4	4.06	3.56	7.62	0.50	13
P5	3.46	3.72	7.18	–0.26	15
P6	3.52	4.14	7.65	–0.62	12
P7	3.48	4.22	7.70	–0.74	11
P8	3.80	4.95	8.75	–1.15	2
P9	3.94	3.99	7.93	–0.05	9
P10	4.38	4.25	8.63	0.13	3
P11	4.84	3.37	8.21	1.47	6
P12	4.35	3.99	8.34	0.36	4
P13	3.53	3.80	7.32	–0.27	14
P14	3.73	4.55	8.28	–0.82	5
P15	3.67	4.33	7.99	–0.66	8
P16	4.47	5.42	9.89	–0.95	1

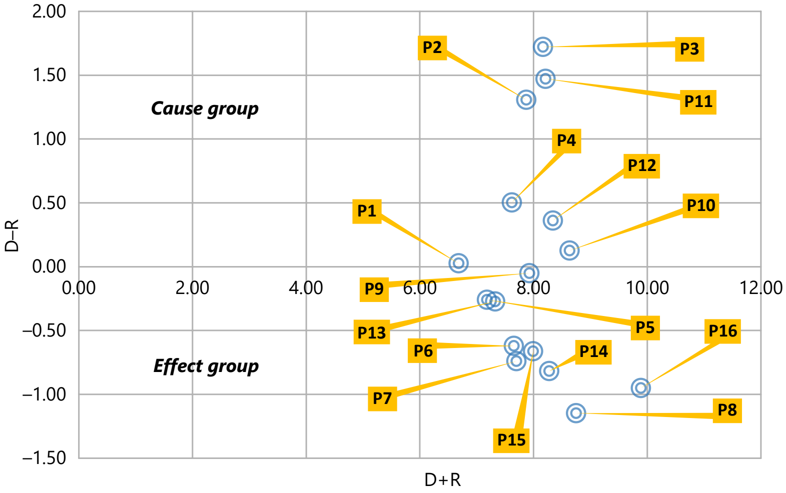

Figure 3. Causal inter-relationship diagram

The practices: corporate social responsibility, management commitment, technological integration and innovation, flexible manufacturing systems, life cycle assessment, distributed localized manufacturing, human-centric and collaborative systems were found to be causal practices. Whereas practices: circular economy initiatives, collaboration and information sharing, adoption of renewable energy, simulation, sustainable manufacturing systems, reverse logistics, mass personalization, supply chain transparency, and ESG compliance were found to be effective practices. The DEMATEL results are consistent with the MICMAC classification. Practices that act as drivers in MICMAC, such as corporate social responsibility, management commitment, technological integration, and innovation, also appear in the causal group in DEMATEL. Practices that are classified as dependent in MICMAC, such as supply chain transparency and ESG compliance, emerge as effect practices. This comparison shows that the combined use of MICMAC analysis and the DEMATEL approach offers a more holistic understanding of practices.

5. Discussion

The objective of the study is to identify the supply chain practices in the context of I5.0 to build a net-zero and resilient supply chain. The hierarchical structure between the practices is assessed by applying the ISM approach. Then prioritization technique DEMATEL is applied to explore the causal interrelationship among the various practices. The hierarchical structure assessed through the ISM approach shows that management commitment is a key practice that can help manufacturing organizations to build a net-zero and resilient supply chain in the context of I5.0. Management commitment helps to promote the culture of sustainability, innovation, and strategic alignment. This is important to integrate advanced technologies and sustainable practices, which are essential to achieve the goals of I5.0 (Rane et al., 2025). Similarly, corporate social responsibility is also important as it helps to promote ethical leadership and community empowerment, which ensures that industrial development is aligned with the human-centric values and long-term stakeholder engagement (John et al., 2026). Transparency and accountability through ESG frameworks are important to achieve net-zero goals, with policymakers and managers playing a key role in strategy implementation and overcoming related challenges (Truant et al., 2024). Through ESG principles, organizations can improve their operational efficiency, reduce emissions, and promote responsible practices (El Jaouhari et al., 2023). Therefore, EGG compliance practices have the highest D+R score and ranked 1 among all practices. Simulation, which is at rank 2, plays an important role in achieving net-zero supply chains by enabling firms to model and predict energy use and carbon emissions under different manufacturing and distribution scenarios. This supports data-driven decision-making for sustainable operations (Malliaroudaki et al., 2023). It models complex systems and evaluates trade-offs between environmental impact, operational efficiency, and improves strategic decision-making (Silva et al., 2023). Life cycle assessment is at rank 3 and supports net-zero supply chains by quantifying emissions across a product's life cycle, enabling data-driven strategies aligned with SDG 13 on climate action (Yadav et al., 2024). It enables supply chains to identify emission hotspots across a product's life cycle and adopt targeted mitigation strategies. Integrating LCA helps organizations reduce greenhouse gas emissions and align with net-zero goals effectively (Chen et al., 2026). I5.0 promotes human-centric and collaborative systems that enhance stakeholder engagement and ethical decision-making. This shift addresses Industry 4.0's limitations and supports resilient, sustainable supply chains aligned with net-zero goals (Grosse et al., 2023).

A human-centric approach in I5.0 improves collaboration and resilience, and addresses economic and social sustainability challenges in supply chains. It supports net-zero goals by enabling adaptive responses to disruptions and workforce demographic shifts (Castagnoli et al., 2024). Smart product platforming powered by AI and GenAI enables mass personalization, aligning product design with sustainability goals for net-zero supply chains. By integrating big data and machine learning, it ensures flexible, eco-friendly production tailored to consumer needs, supporting circular economy principles (Akhtar et al., 2024). Further, mass personalization through distributed localized manufacturing supports net-zero supply chains by reducing transportation emissions and optimizing resource use. It improves supply chain efficiency and resilience through local production, aligning customization with sustainability goals (Wang et al., 2024). Distributed manufacturing systems are important for net-zero supply chains as they decentralize production, reducing transportation-related emissions and enhancing resource efficiency. By overcoming organizational and sociocultural barriers, it can improve environmental performance while promoting local resilience and sustainability (Gupta et al., 2023). Technological integration is important for achieving carbon neutrality in manufacturing supply chains (Dohale et al., 2024). It enables firms to align lean, green, and digital strategies to achieve net-zero supply chains. Using the VRIO framework, companies can identify and implement value-creating digital solutions that support both sustainability and competitive advantage (Yadav et al., 2023). Supply chain transparency enables traceability, promotes trust and accountability, which is essential for adopting net-zero strategies. It also supports waste reduction, carbon emission control, and enhances security through blockchain-based monitoring (Yadav et al., 2025a).

Sustainable manufacturing systems are also important and ranked 9. It enables the transition to net-zero supply chains by integrating eco-innovations that lower emissions. Incentives, expertise, and funding are key enablers that support this shift while aligning with global sustainability goals (Dohale et al., 2024). Management commitment plays an important role in developing net-zero carbon supply chains by shaping culture, aligning strategies, and driving stakeholder collaboration. In the European manufacturing sector, strong leadership ensures effective resource allocation and supports transformative decarbonization efforts (Steiner et al., 2024). The adoption of renewable energy is important for net-zero supply chains as it ensures clean electricity and reduces reliance on fossil fuels. It significantly lowers carbon emissions and supports climate neutrality by mitigating both CO_2 and non-CO_2 greenhouse gases across the supply chain (Guntuka et al., 2024). Supply chain collaboration is essential to achieve SDGs and net-zero goals by improving resource utilization and operational performance. Through collaborative innovation and information sharing, it enables better decision-making and efficiency, supporting carbon reduction efforts across the supply chain (Chauhan et al., 2022). There is a growing need for Flexible manufacturing systems to adapt to changing market demands and support net-zero supply chains. By integrating Industry 4.0 technologies, it enhances responsiveness, reduces waste, and optimizes resource use, enabling firms to meet environmental goals while staying competitive (Höse et al., 2023).

Reverse logistics is at rank 14. It plays an important role in achieving net-zero supply chains by enabling efficient resource recovery and minimizing waste. When integrated with circular economy principles and sustainability practices, it reduces environmental impact and enhances overall supply chain performance (Salas-Navarro et al., 2024). Transitioning to a circular economy is important to achieve net-zero emissions, as it reduces CO_2 output by minimizing waste and maximizing resource reuse. The shift from linear to circular models strengthens supply chain sustainability and supports global climate goals (Hailemariam & Erdiaw-Kwasie, 2023). Incorporating corporate social responsibility into supply chain strategies improves performance and resilience, especially in volatile environments like the automotive sector. Prioritizing it is important to achieve sustainable, net-zero supply chains and aligned with environmental objectives (Lin, 2023).

6. Implications of the study

The findings of the present study provide a holistic understanding of I5.0 practices, interdependencies, and their strategic role to achieve net zero and resilient supply chains. Based on these insights, implications for theory, managers, and public policy for emerging economies have been discussed. The implications are discussed below across three dimensions.

6.1. Theoretical implications

The present study contributes to the theoretical advancement of I5.0 literature by structurally analyzing the relationship among supply chain practices to build net-zero and resilient supply chains in the I5.0 context using the ISM and DEMATEL approach. The present study extends the existing work on circular and sustainable supply by identifying practices in the context of I5.0 that can operationalize circularity, resiliency, and decarbonization in supply chains.

Through the ISM-DEMATEL approach, this study offers a theory-driven structural model that reveals hierarchical levels and causal interrelationships among these practices. Further, the study considered the perspective of emerging economies on I5.0 discourse and shows how these practices can be helpful for emerging economies to build net-zero and resilient supply chains.

6.2. Implications for the managers

First, the hierarchical model shows that management commitment, corporate social responsibility are the foundational practices, so leadership should prioritize clear climate and human-centricity targets. Industry reports from the World Economic Forum also noted that supply chain decarbonization is a major business opportunity rather than just a compliance cost, with net zero chains adding only a small markup to the end consumer prices (Hobley et al., 2021). Managers can therefore justify early investment in digital technologies, renewable energy, and circular design as sources of resilience, cost efficiency, and reputation. Our results also indicate that flexible manufacturing systems, simulation acts as an important practice, so firms should pilot digital twins, scenario-based planning, and shared data spaces before scaling more advanced circular and net-zero initiatives. In this context, Global surveys also show that most executives now see supply chain sustainability as a competitive advantage, which aligns with our finding that circular economy initiatives, life cycle assessment, and sustainable manufacturing are important to build net-zero and resilient supply chains (Delloite, 2023). Managers should integrate circular economy and life cycle assessment principles into new product development, sourcing, and logistics contracts, and use reverse logistics practices to recover value and reduce emissions across the product life cycle. The prominence of distributed localized manufacturing and supply chain transparency in the model suggests that firms need to reconfigure networks towards regional hubs while also investing in end-to-end traceability through digital platforms and data standards. As the top of the hierarchical model, human-centric and collaborative systems, mass personalization, and ESG compliance emerge as the outcomes, which means managers should design workforce development, safety, and skills programs (Breque et al., 2021). Managers should also engage suppliers and SMEs in capability building, since industry analyses also show that global supply chains cannot reach net zero without supporting smaller partners through finance, data, and technology sharing (World Economic Forum, 2022).

6.3. Implications for policymakers

For the policymakers, the hierarchical framework highlights where public interventions can most effectively guide I5.0 transition toward circular, net-zero zero and resilient supply chains. First, the management commitment and corporate social responsibility suggest the need for stable, long-term climate and social regulations that give firms clear directions on net zero and human-centric goals, consistent with the European Union's I5.0 vision of aligning industry with worker well-being (Breque et al., 2021).

Second, our results support policies that incentivize technological integration, simulation, and flexible manufacturing through targeted subsidies, green tax credits, and support to build digital infrastructure (Henrich et al., 2022). Global evidence shows that decarbonizing the top eight global chains could cut more than 50% worldwide emissions with only a 1–4% cost increase for end consumers, which underlines the importance of carbon pricing, disclosure mandates, and Scope 3 reporting standards for buyers and suppliers (Hobley et al., 2021).

Third, circular economy practices and reverse logistics are important practices. Therefore, policymakers should design extended producer responsibility schemes, material passport standards, and circular public procurement rules to unlock these business models. Since SMEs play an important role in the global supply chain yet often lack resources, policy packages should combine finance, capability building, and digital platforms so that smaller firms can participate in I5.0 transition and contribute to national net-zero and resilience strategies.

7. Conclusions

The present study examines how supply chain practices in the context of I5.0 can help to build net-zero and resilient supply chains. In this study, we used a three-phase approach that combines literature review, ISM-MICMAC, and the DEMATEL approach. A hierarchical model is developed based on the ISM-MICMAC approach, and the inter-relationship among practices is assessed through the DEMATEL approach. The results show that corporate social responsibility, management commitment, and technological integration and innovation form the foundational practices that shape other practices. Mid-level practices such as flexible manufacturing systems, circular economy initiatives, collaboration and information sharing, adoption of renewable energy, simulation, and sustainable manufacturing help to build net-zero and resilient supply chains. At the top of the hierarchical model, human-centric and collaborative systems, mass personalization, and ESG compliance emerge as dependent practices that help to achieve net-zero outcomes. The DEMATEL analysis validates this structure by classifying corporate social responsibility, management commitment, technological integration and innovation, flexible manufacturing systems, and life cycle assessment as causal practices with a higher prominence score. While circular economy initiatives, the adoption of renewable energy, and ESG compliance the effective practices. Also, this study highlights how these practices across the various supply chain stages can ensure long-term economic as well as environmental benefits.

Despite of contributions of the study, we also acknowledge certain limitations such as reliance on expert inputs and the scope considered in the study. Future research can address these limitations by incorporating methods such as Bayesian modelling and sensitivity analysis to validate the robustness of the study. Also, longitudinal studies across sectors and other geographical regions can help to provide more insights into how practices in the context of I5.0 can impact different industry contexts. The findings of the present study provide valuable insights for researchers, policymakers, and practitioners seeking to improve the supply chain practices in a net-zero future. This study will serve as a strategic foundation for organizations to align their digital, environmental goals through supply chain practices in the context of I5.0.

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