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Research article

Redefining supply chain dynamics: digitization and green innovation as catalysts for energy supply chain resilience under UN-SDGs

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Abstract: Considering UN-SDGs 2030, increased globalization, and consumer concern for environmental sustainability, digitization and green innovation have become important instruments for companies to promote energy supply chain resilience (ESCR). This study aimed to check the effect of digitization and green innovation on ESCR through the lens of UN-SDGs. Initially, indicators for digitization, green innovation, and ESCR were collected from a literature review and confirmed through the Delphi methodology, which was subsequently used to analyze the data using the ISM-MICMAC methodology. Based on a hybrid methodology of ISM-MICMAC and Delphi through a unified threshold rule with its three rounds, data collected from 15 experts/stakeholders from academia, industry, and policy domains highlighted that "renewable energy integration", "sustainable sourcing", and "eco-friendly packaging" are the most important indicators of green innovation affecting ESCR. All indicators of digitization indirectly affect ESCR, except "optimization of SC", which is directly associated with it. At the 5th level of the ISM model, it was found that different indicators of green innovation and digitization can be implemented in four distinct stages, which will also help policymakers implement stepwise initiatives to promote ESCR. Furthermore, these key drivers will serve as a decision-support system for promoting ESCR. This research offers policymakers and practitioners actionable insights by identifying the pathways through which digitization and green innovation contribute to operational efficiency, sustainability, and long-term resilience in energy supply chains.

Keywords: supply chain sustainability; energy supply chain resilience; supply chain digitization; green innovation; decision support; UN-SDGs; ISM-MICMAC
Mathematics Subject Classification: 90C26, 90C30

1. Introduction

Globalization and increased customer awareness of environmental issues have led organizations to integrate digital and green technologies into their supply chains; hence, this is an agenda that matters nowadays. This ever-increasing acceleration toward digitalized and sustainable technologies is a primary theme of modern sustainability motivation, efficiently combining the twin aims of productivity enhancement and eco-safeguarding in global supply chains [1]. The trio of supply chain digitization (SCD), green innovation (GI), and energy supply chain resilience (ESCR) has come to the fore in the sustainability push. The meeting point between the UN-SDGs, a universal call for action to end poverty and protect the planet for all, is even more relevant against this background [2,3]. SCD is defined by the adoption of technology, driving progress toward many SDGs, such as Goals 9 (Industry, Innovation, and Infrastructure) and 12 (Responsible Consumption and Production). SCD effectively enhances operational efficiency, minimizes waste, and maximizes resource utilization, thereby fostering sustainable economic development and strengthening industrial resilience [4,5]. Thereby, SCD can enhance the efficiency of operations, reduce waste generation, and mitigate resource use to ensure sustainable economic development and industrial strength [6].

Similarly, GI (achieved through eco-friendly products, processes, and business models) helps in achieving SDG3 (Good Health and Well-Being), SDG9 (Industry, Innovation, and Infrastructure), and SDG12 (Responsible Consumption and Production) as well as through eco-friendly products, processes, and business models [7]. Industries will make a difference if they innovate and incorporate ecology into product design and production. This approach promotes climate change mitigation, sustainable production, and social inclusiveness in industrialization [8]. Additionally, ESCR is also connected to supporting SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) [9]. Use of renewable energy sources, energy efficiency supply chains, and reducing GHG emissions in supply chains are some of the global contributions to combat climate change and build resilience to environmental disasters, as well as developing sustainable infrastructure [10]. The SCD and GI both play a key role in ESCR strategy in the framework of the UN-SDGs [11]. Metaverse technology, combined with systematic process optimization, will significantly drive SDG7 through improved energy efficiency of global supply chains [12]. It also facilitates the transition toward renewable energy sources within supply chains. Furthermore, GI, which focuses on developing innovative and eco-friendly products, aligns with SDG

9 and SDG 12. It fosters the integration of energy-efficient solutions throughout the supply chain network [13]. Through the synergistic collaboration of these forces, organizations can achieve multiple SDGs simultaneously (as shown in Figure 1), thereby promoting sustainable and green growth while enhancing energy resilience within their supply chains [9]. Although studies have been conducted on individual elements, such as GI and SCD, comprehensive examinations that consider the synergistic impact of both technologies in advancing the ESCR within the framework of the SDGs are still scarce, highlighting a gap in existing literature.

Very few studies have worked on the integration of supply chain practices and SDGs: Zhou, Govindan [2] worked on the association of knowledge-driven GI and SDGs; Centobelli, Cerchione [14] developed a framework for investigating the role of SDGs in promoting green supply chain practices and digital technologies; and Wang, Abbas [15] investigated the moderating role of green organizational culture between green knowledge management and SDGs. However, the integrated effect of SCD and GI for establishing ESCR under the umbrella of SDGs has not yet been studied. Considering this study gap, this study attempts to address the following research questions:

1: What is the effect of SCD on ESCR under the scope of UN-SDGs?

2: What is the effect of GI on ESCR under the scope of UN-SDGs?

3: What is the combined effect of SCD and GI on ESCR under the scope of UN-SDGs?

In this context, this study aims to contribute to a better elucidation of the concept of sustainable development in supply chain management. Against this backdrop, the purpose of our study is to explore the complex interactions between SCD, GI, and ESCR within the SDG framework. By investigating their correlations, tradeoffs, and relationships, this paper contributes significantly to the literature by offering helpful implications for further development of sustainable strategies in a supply chain management setting. So equipped, organizations might better navigate a future in which economic health, environmental preservation, and social well-being can co-exist (SDGs).

This study makes several contributions. First, from a theoretical perspective, it connects stakeholder theory to the role of salient entities (policymakers, supply-chain leaders, regulators, and academia) in pressing for the use of SCD and GI to promote ESCR. Second, it develops methodology by combining the Delphi method and the interpretive structural modeling (ISM) technique with MICMAC to offer a systematic mode for discovering key drivers and their complex interrelations in a linked-structured hierarchy. Ultimately, it provides value by outlining a step-by-step roadmap that companies and public officials can follow to align digital and green transformation with the UN Sustainable Development Goals (UN-SDGs). These interconnected contributions strengthen both scholarly debates and day-to-day choices that shape sustainable supply chains.

Figure 1. SDGs associated with SCD, GI, and ESCR.

The remaining paper is structured as follows (Figure 2): In the first section, the theoretical background associated with problem identification and literature review is presented. The next section presents a literature survey for variable identification and filtering using the Delphi method. Further, interpretive structural modeling and MICMAC are explained. Finally, results are interpreted in the light of study implications.

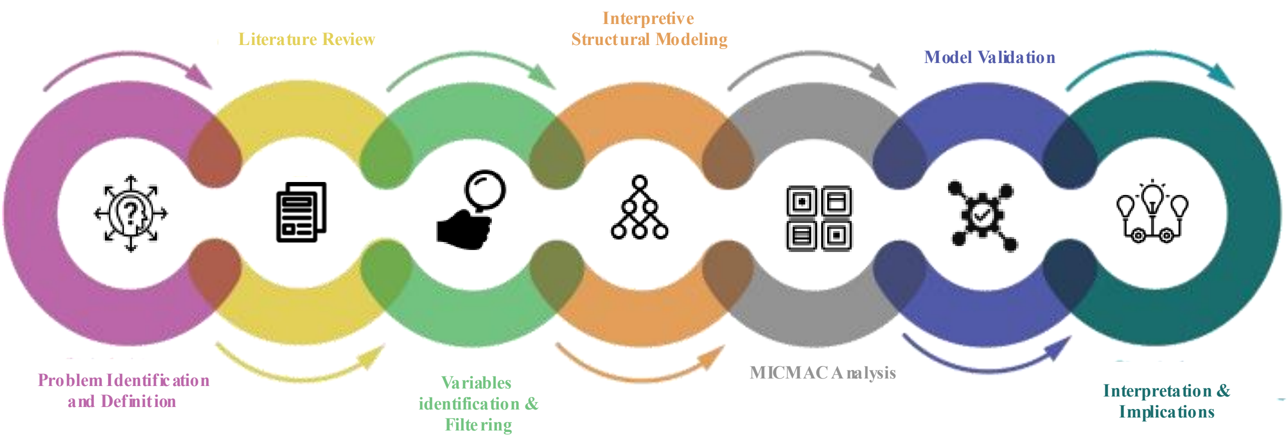

Figure 2. Step-by-step study approach (Author generated).

2. Theoretical background and literature review

2.1. Problem identification and research gap

Despite the numerous studies on sustainable supply chains, the association between SCD and GI with ESCR still needs to be investigated, especially to highlight the digital and eco-friendly technologies that need to be implemented in the manufacturing sector to boost ESCR. In the given scenario, SCD and GI might provide multiple benefits. Some researchers have proposed investigating the relationship between these factors. For instance, Bagherian, Gershon [16] investigated the association between digitization and energy sustainability, and their research recommended exploring the combined effect of GI and digitization for promoting energy resilience, especially in the supply chain context. However, a scarcity of empirical studies is found in this regard, resulting in an understudied impact of SCD and GI on ESCR. This study bridges the aforementioned gap and aims to investigate the effect of SCD and GI on ESCR within the context of the SDGs. Existing studies on these variables are described below.

2.2. Theoretical framework

This research is based on stakeholder theory, which posits the notion that firms cannot operate solely in light of their own efficiency or profit from internal operations but must also heed the competing groups located beyond the boundaries of a company that can ultimately determine a firm's long-term survival [17]. Stakeholders range from customers, suppliers, employees, and governmental institutions, including regulators, to the local community; each stakeholder group exerts a different level of pressure on companies [18]. In the case of ESCR, the pressure is more intense. Disruptions in the supply chain, market volatility, and growing environmental sensitivities force all parties to the table. Stakeholder theory stipulates that organizations acquire legitimacy and ensure stability by dealing with issues in a proactive and transparent way [19]. SCD is swiftly becoming the best software for firms seeking to increase their ESCR. When companies digitize their records, they gain clearer, faster, and more accountable perspectives on their full energy supply chain, all the way back to its upstream origins through final delivery. By enhancing visibility, traceability, and accountability, we reduce the odds of surprises and disruptions while concurrently strengthening trust with investors, customers, and regulators alike. Meanwhile, GI responds to growing stakeholder demand for cleaner options along all aspects of energy generation and distribution [20]. When companies integrate SCD with GI, it enables them to deliver not only ESCR but also embed their business activity within established global contexts such as the UN Sustainable Development Goals (UN-SDGs). The stakeholder theory further supports the notion that connecting technology upgrades with sustainability initiatives is more than a good intention; it is also good for business.

Finally, the approach is effective for structuring complex relationships among several actors, using ISM-MICMAC analysis to map such a network of stakeholders. It lets us know what drivers and dependencies should be considered as material, through the lens of stakeholders. The integration of the stakeholder theory and ISM-MICMAC approach provides a complete framework and step-by-step process to direct our study. Thus, the study hypotheses (Section 2.4) were analyzed using stakeholder theory and, particularly, in ISM-MICMAC analysis, as it only works if stakeholders are included in the decision-making process, providing holistic results.

2.3. Why are SCD and GI important for ESCR?

SCD and GI are essential for ESCR, since they can change the mechanisms of energy production, distribution, and utilization. Adoption of advanced technologies and approaches for renewable energy integration, energy-efficient solutions, and smart grid systems would reduce reliance on fossil fuels and reduce carbon dioxide (CO_2) emissions. Moreover, SCD is more than just a form of improving transparency and making vehicles flow; it facilitates the transport of green energy from sources to the grid and industries for sustainable living. Through the development of SCD and GI, the business and the community can function in a manner that shrinks our environmental footprint, expanding opportunities to create economic revitalization, secure energy resources, and improve social well-being for today's citizens as well as future inhabitants. Thus, the principle of SCD and GI associated with SDGs is significant.

Firms could promote ESCR through SCD and GI in a number of ways. First, they can leverage advanced technologies, including Internet of Things (IoT), artificial intelligence (AI), and Blockchain, to optimize logistics routes, reducing idle time and energy consumption. Also, the development of environmental packaging technology and the application of a sustainable circular economy can play a role in minimizing material waste and energy consumption in supply chains. Moreover, investing in renewable energies (solar and wind power) for manufacturing plants and warehouses can contribute to reducing dependency on natural resources and greenhouse gas emissions. Focusing on innovation and digitization of supply chains may lead to new business processes, products, and even business models, favoring energy efficiency or the protection of the environment over other values. Finally, by combining SCD and GI, firms can realize their energy efficiency objective, become competitive in the marketplace, enhance their brand image, and help create a world where public goods are safeguarded.

Current studies demonstrate the positive correlation between digital transformation and sustainability. For example, Arezoo [21] studied the efficiency of AI in minimizing shipping routes and saving energy for delivery companies. According to Akinsemolu [22], greener and flexible supply chains can be achieved through combining eco-friendly packaging with digital production techniques. Wang, Abbas [15] also noted that virtuous companies gain more advantages through digital tools in the achievement of UN-SDGs. Despite these encouraging observations, there is limited research on the interaction between SCD and GI affecting the ESCR, as well as the use of the SDG approach. This study addresses this gap by integrating sound methods with a stakeholder-focused analysis.

2.4. Hypotheses development (Impact of SCD and GI on ESCR)

The academic literature emphasizes that SCD and GI strategies contribute to ESCR and highlights the issues surrounding their implementation and the effects of such practices. Many scholars have shown that IoT, AI, and big data analytics help in enhancing the efficiency and power sinking through advanced technology application in supply chain operations [21]. An example, as given by Oudani, is that of IoT-based sensors and real-time data analysis that improve energy management in supply chains. Such integrations can result in significant reductions in energy consumption and carbon emissions. It also evaluated AI algorithms in route optimization and vehicle scheduling, showing remarkable results in energy preservation and fuel savings among transportation networks. Furthermore, both academics and practitioners have underscored the importance of SCD and GI within companies in order to carry out ESCR activities across their supply chains. The variation of environmental performances as a function of GI preferences is positively correlated with a decrease in energy consumption and greenhouse gas emissions [22]. Furthermore, Burke, Zhang [23] highlighted green product design, digital manufacturing processes, and eco-friendly packaging to improve energy efficiency, environmental sustainability, and supply chain sustainability.

The wider literature regarding the impact of SCD and GI on ESCR highlights the importance of adopting a holistic approach, which stimulates technological developments, improves organizational abilities, and forms collaborative modes among stakeholders. Despite the highlighted studies, there are no studies evaluating the impact of SCD and GI on ESCR, particularly considering expert opinion, which is the main objective of this research. Furthermore, in this work, the impact of SCD and GI on ESCR is examined in the context of stakeholder theory. As sustainability concerns increasingly shape ESCR decisions, various stakeholders (e.g., supply chain executives, directors, IT and market consultants, energy economists) exert growing pressure on organizations to adopt environmentally friendly practices and mitigate the risks posed by climate change and resource scarcity.

Based on the above text, this study proposes three main hypotheses as follows:

- H1: GI has a positive influence on ESCR.
- H2: SCD positively influences ESCR.
- H3: The combined effect of SCD and GI produces stronger resilience than either construct alone.

These propositions guide the structuring of relationships in the ISM model and the categorization of variables in the MICMAC analysis.

3. Research methodology

This study investigated the dependence of SCD on GI and ESCR by an integrated method, namely the Delphi and ISM-MICMAC technique. The Delphi technique is an appropriate method for this research as it collects judgments from responses of a neutral panel of experts over rounds, in which participants can hone their views until a clear agreement emerges [24]. The ISM model allows drawing a vivid hierarchical network of influences among criteria, such as SCD, GI, and ESCR, transforming a complicated system into an understandable diagram [25]. Finally, the MICMAC method is a widely used technique for classifying metrics into "driving", "linkage", "dependent", and "autonomous" categories to confidently identify the most important areas for action [26]. By bringing together these three strategies, results are validated, relationships are mapped, and metrics are classified, leading to a more reliable study design. Four steps are involved in this methodology [27]: 1) Identification of key constructs of each variable with the help of a systematic literature review. 2) Delphi methodology for filtering the relevant constructs of variables. 3) Development of a hierarchical structure of association between SCD, GI, and ESCR using ISM methodology. 4) MICMAC analysis. All steps, along with their subsequent activities, are shown in Figure 3. This research has been granted ethical clearance by the Institutional Review Board (IRB), reference number XAIU202407, dated November 12, 2024, of the School of Business at Xian International University, and was conducted in accordance with the Helsinki Declaration's ethical standards. Informed written consent was obtained from all study participants, who claimed their understanding of the study's purposes and participated voluntarily. The respondents were assured that their identities and responses would be kept confidential for the best interests of academic integrity in every possible manner. Furthermore, they were informed about the relevance of the study, its implications, and their position as subjects, and were not financially remunerated for their participation. Respondents were also told that they could decline to answer any question and terminate the interview at any time. The collection time period was between November 2024 and February 2025.

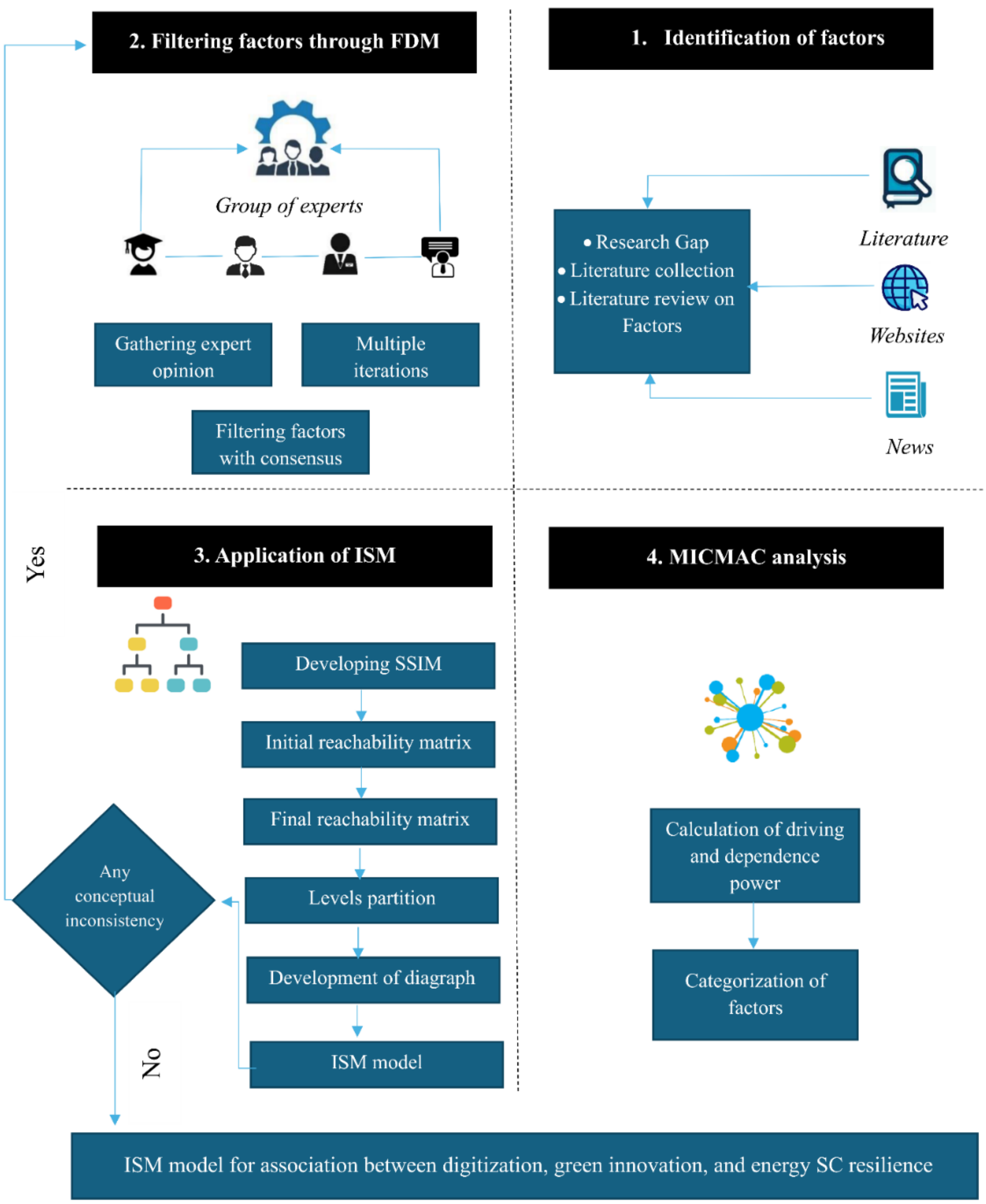

Figure 3. Research methodology (Author generated).

3.1. Variable identification (step 1: systematic literature review)

A literature review is a systematic, transparent, and reproducible process of classification, evaluation, analysis, and interpretation of the relevant research. Following this approach, 70 papers were selected for detailed review. A total of 19 key constructs relevant to sustainability or the SDGs were identified from the selected studies and are summarized in Table 1. The construct frequency in the table indicates the prominence of each construct in the reviewed literature. This was achieved by tabulating the number of studies that approached each factor in relation to digitization and green innovation as catalysts for energy supply chain resilience under the UN-SDGs. That is, designations labeled as "High" were widely cited across multiple sources, while "Moderate" or "Low" frequencies represented less common, yet still pertinent, mentions. Once the important constructs had been identified from the literature, a filtering of the most relevant ones was undertaken. This was accomplished by applying the fuzzy Delphi method (FDM), which is further elaborated upon in the next step.

Table 1. Key constructs of the study and relevant SDGs.

Code	Construct	Description	Reference	Impacted UN-SDGs
ESC1	Energy source diversification	Energy displacement through technology mixes of energy reduces reliance on any one source.	[28]	SDG7
ESC2	Infrastructure interconnectivity	Resilient infrastructure with redundancies and connectivity to improve resilience	[29]	SDG9
ESC3	Flexibility and adaptability	Respond quickly to changes and disruptions	[30]	SDG9, SDG12
ESC4	Contingency measures	Clearly defined emergency preparation and response plans in SC for energy	[31]	SDG7
ESC5	SC information sharing	Exchange of information between all relevant role-players to prevent/manage risk proactively	[32]	SDG17
GI1	Carbon reduction	Carbon footprint reduction of SC functions	[8]	SDG3, SDG13
GI2	Waste reduction and recycling	Applying methods of waste minimization and closed-loop systems	[33]	SDG3, SDG12
GI3	Eco-friendly packaging	Implementation of sustainable packaging solutions, for instance, biodegradable materials, to enable packing design efficiency	[34]	SDG12
GI4	Sustainable sourcing	Favoring ethical and sustainable suppliers	[35]	SDG8, SDG12
GI5	Renewable energy integration	Incorporate clean energy sources for less reliance on fossil fuels	[35]	SDG7, SDG13
GI6	Eco-design SC processes	Applying eco-design to reduce environmental impact.	[33]	SDG9
D1	Real-time tracking	Real-time understanding of SCs to support stakeholders' monitoring parties	[36]	SDG9, SDG12

Continued on next page

Code	Construct	Description	Reference	Impacted UN-SDGs
D2	Supply chain analytics	Leverage predictive data analytics to obtain actionable insights	[37]	SDG8, SDG9
D3	Cloud-based infrastructure	Seamless collaboration and sharing of information between supply chain partners		SDG9, SDG17
D4	IoT integration	RFID with GPS, SC can be incorporated	[38]	SDG8, SDG9
D5	Blockchain technology	Transparent traceability of product flow in the SC	[38]	SDG9, SDG16, SDG17
D6	Automation and robotics	Streamline routine operations with robotics and automation solutions	[39]	SDG8, SDG9, SDG12
D7	Optimization of SC	Resource allocation optimization through simulation, modeling, and optimization of SC operations	[40]	SDG9, SDG12
D8	Artificial intelligence & machine learning	SC data processing for decision-making and better service efficiency	[37]	SDG8, SDG9, SDG16

Following established best practices [41], our main aim was to conduct a literature review on supply chain digitization, green innovation, and energy supply chain resilience. Relevant bibliographic databases, including Google Scholar, Science Direct, Web of Science, Scopus, Emerald, and Springer, were queried using keywords such as "Supply Chain Digitization", "Green Innovation", and "Energy supply chain resilience" to obtain a comprehensive list of publications. This produced 850 articles. For a systematic literature review (SLR), de-duplication and "counting logic" techniques were conducted to filter out the relevant articles. Each article was included if it met the following inclusion criteria: (1) publication in peer-reviewed journals, (2) direct relevance to SCD, GI, or ESCR, (3) publication within the last 10 years, and (4) empirical or theoretical contributions linked to UN-SDGs. Exclusion criteria included: (a) non-English articles, (b) studies without a supply chain focus, and (c) duplicate or redundant publications. After applying these criteria, 70 articles were included in the detailed analysis. This rigorous approach ensured relevance and methodological validity.

3.2. Variables filtering (Delphi methodology)

The Delphi method (DM) has been applied in multiple fields of research as a means to capture experts' knowledge. However, although it is a strong model, it has limitations; namely, it can be time-consuming, contributing to delayed decision-making [42]. Other limitations include the possibility of poor consensus, high implementation costs, and its reliance on expert opinion, which may result in different opinions [43]. To address these problems, Murray, Murray, Pipino [43] introduced the fuzzy Delphi method (FDM), which combines fuzzy theory with the traditional Delphi method. Hsu and Yang [44] also observed that including fuzzy numbers could eliminate vagueness to some extent, facilitating decision-making. FDM is an increasingly popular process in business research, particularly where professional judgment is needed to identify barriers, strategies, and drivers [35]. FDM allows experts to sharpen their intuitions and narrow the scope of explanatory variables, more easily isolating those that matter [45]. This approach also fosters consensus among respondents, thereby increasing the reliability of the results. In the current study, FDM was applied to test and confirm the prominent indicators of digitization and green innovation on ESCR through the lens of UN-SDGs. According to the experts' feedback, Figure 4 indicates that all indicators obtained values greater than the threshold of 40. As such, all indicators mentioned in Table 1 are necessary and none are irrelevant. A more detailed application of the proposed FDM method for the identification of indicators regarding digitization and green innovation on ESCR through the lens of UN-SDGs was elaborated as follows.

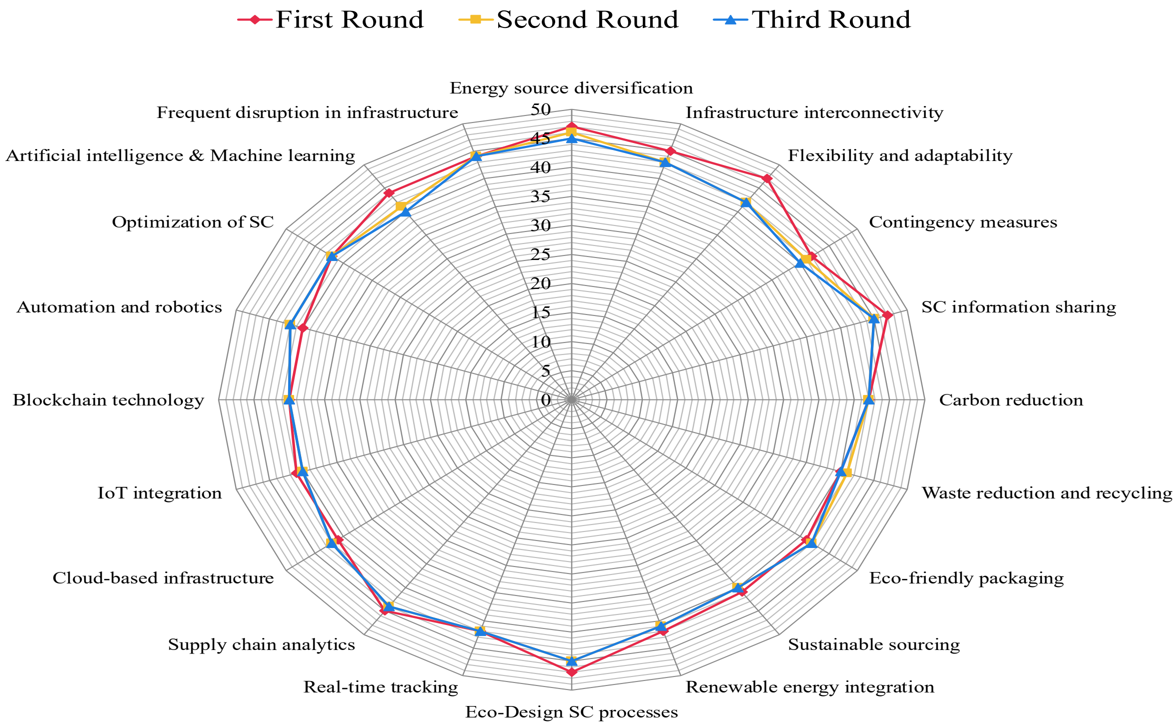

Figure 4. Results of Delphi methodology (Author compilation).

3.3. Data collection by survey distribution

Questionnaires were distributed among SC industry experts. The expert panel comprises a sample of 15 participants, as described in Table 2, with representation from both academia and industry, including a supply chain manager, an IT consultant, an economist, and a professor, among others, ranging from 7 to 22 years of experience. Experts were selected based on (1) a minimum of 7 years of professional or academic experience, (2) expertise in supply chain management, energy systems, or sustainability, and (3) representation across different industries and institutions. In this study, a sample size of 15 is consistent with previous ISM Delphi studies, which have used 10–20 experts, as described by Iqbal, Ma [25], Ahmad, Zhu [27], Iqbal, Ma [35], Usmani, Wang [45]. Experts from various countries and sectors participated to ensure representation.

Table 2. Expert panel profiles.

Sr#	Age	Gender	Education level	*Industry/academia experience	Designation	Company/university size
1	35	Male	PhD in Logistics	10 years	Researcher	Large University
2	42	Female	Master's in IT	15 years	Technology expert	Medium corporation
3	38	Male	MBA	12 years	Supply chain manager	Small corporation
4	29	Female	Bachelor's in engineering	7 years	Data analyst	Start-up
5	45	Female	PhD in Economics	20 years	Policy analyst	Large corporation
6	33	Male	Master's in supply chain management	8 years	SC consultant	Medium corporation
7	40	Female	PhD in Business	18 years	Professor	Large university
8	37	Male	Master's in operations research	14 years	Supply chain analyst	Small corporation
9	31	Female	Bachelors in finance	9 years	Financial analyst	Medium corporation
10	48	Male	MBA	22 years	Director	Large corporation
11	36	Female	Master's in marketing	11 years	Market researcher	Medium corporation
12	43	Male	PhD in Computer Science	19 years	Professor	Large university
13	34	Female	Bachelor's in supply chain management	10 years	Operations manager	Small Corporation
14	39	Male	Master's in economics	16 years	Economist	Medium corporation
15	32	Male	Bachelor's in business administration	7 years	Project manager	Small corporation

*Note: This panel of experts comprised professionals from different universities and institutes with over 7 years of experience in energy supply chain, digital transformation, and sustainable innovation positions in areas such as energy, logistics, and technology.

The Delphi method comprised three rounds. Qualitative criteria of convergence were applied to the three Delphi rounds (e.g., stability of central tendency or reduction in dispersion). Consensus was specified by the cut-off point of 40, as recommended in previous literature [26]. All 19 identified indicators were above this threshold value (Figure 4) and were preserved for ISM-MICMAC analysis. Hierarchical relationships among indicators were structured using the ISM technique. Additionally, the MICMAC analysis stratified the variables into driving, linking, dependence, and autonomous clusters. This dual approach improves both the reliability and the interpretability of the results. Throughout this process, expert-content suggestions concerning indicators to be modified or included were considered for relevance and perspective. A five-point Likert scale was applied to the questionnaire in order to lower potential response bias and to increase the validity of the collected data. The Likert scale has been consistent in earlier studies and is a comprehensive scale to evaluate the importance of a construct or factor based on different degrees (e.g., 1 to 5).

3.4. Aggregating expert opinions and formulating the TFNs (triangular fuzzy numbers)

The triangular fuzzy numbers (TFN) calculation method [35] was used in this study. The minimum, most likely, and maximum values of expert opinions were captured using TFNs, allowing a structured approach for considering uncertainty and subjectivity in expert judgment. Geometric means (GMs) were calculated to display the results of TFN in a clear and interpretable way. These geometric means combine experts' judgments and are useful for ordering the TFN in a systematic order. Let $W_j^n = \left(a_j^n b_j^n c_j^n\right)$ represent the preference of the nth expert toward the jth driving indicator of sustainability and UN-SDGs, expressed by means of TFNs. To include n expert opinions, we use Eq. (1) in the following form:

$$W_j = \left(a_j b_j c_j\right) = \left(a = min\{a_{ij}\}, b_j = \frac{1}{n}\sum_{i=1}^{n} b_{ij}, c_j = max\{c_{ij}\}\right) \quad (1)$$

Here, W_j represents the aggregated TFNs, which synthesize the collective opinion of the experts.

3.5. Selection of indicators

Finally, the last step of FDM analysis shows the TFNs of each indicator, its GMs, and the minimum and maximum of expert judgments. To find the top indicators, a standard thumb rule was applied as suggested in [35]. Fundamental drivers were derived in the course of this process, based on the comparison of each construct weight against a threshold value ~w’ w~, which refers to the average weight of all constructs with regard to sustainability and UN-SDGs

$$w_j = \frac{a_j + b_j + c_j}{a}, j = 1,2,3, \dots m \quad (2)\ ^{*1}$$

∗ 1: The weight of each construct and indicator is represented by a crisp value w representing the overall expert preference for sustainability and UN-SDGs indicator j. Following the rule:
Construct j is significant and accepted if aj ≥ w
Construct j is considered negligible and will be discarded if aj < w

In which aj represents the factor score, and w is the threshold value that is set to 40.

After this assessment, all driving forces met or surpassed the threshold value. Thus, all indicators that could be identified were kept for further analysis.

3.6. ISM

Warfield introduced the ISM technique to grasp the contextual relationship among diverse components within a system [46]. Researchers have adopted various MCDM techniques to resolve complex issues, such as VIKOR, TOPSIS, AHP, DEMATEL, and ANP.

However, some unique characteristics of ISM distinguish this approach from others. Iqbal, Ma [25] elaborated on some features of this method, as follows:

- This significant method establishes a smooth relationship between various elements by assessing professionals in specific fields.
- This novel approach develops a hierarchical structure of different elements that are easy to understand.
- This method serves well for expressing the connection of a set of elements in the digraph.
- ISM helps to systematically sequence and detect complex components.

This method has been adopted in different areas, such as construction, manufacturing, medical, engineering, social sciences, and management.

3.6.1. Steps of ISM methodology

Step 1. SSIM

Each pair is related through a structural self-interaction matrix (SSIM), designed based on expert opinions using a structured questionnaire. The questionnaire was given to experts, who were asked to subjectively evaluate the relationships between different indicators. Contact with 35 initial expert respondents was made via various approaches, such as LinkedIn, email, telephone calls, or tweets. To motivate participation, experts were tracked through phone calls and reminder emails. Finally, 15 of the 35 experts agreed to participate, and their opinions were collected through Zoom meetings. This panel of experts included SC experts, consultants, IT engineers, professors, policy analysts, and economists. All experts involved in the panel held academic degrees, were experienced professionals, and had extensive decision-making experience in their field of supply chain management. A full list of the experts is available in Table 2.

Initially, an SSIM was developed using experts' responses. Experts connected two constructs i, j by employing four-letter indexing (S, D, F, G):

$S(i \rightarrow j) =$ The factor i is affiliated with j.

$D(j \rightarrow i) =$ The factor j is affiliated with i.

$F(i \leftrightarrow j) =$ Factors i and j have an affiliation with each other.

$G(i \otimes j) =$ Factor i and j are not affiliated with each other.

The SSIM showing all expert responses regarding different associations between variables is shown in Table 3.

Table 3. Structural self-interaction matrix (SSIM).

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ESC1		F	F	F	F	D	D	D	D	G	G	G	G	D	D	D	D	D	D
ESC2			F	F	F	D	D	D	G	G	G	D	D	D	D	G	G	G	D
ESC3				F	F	G	G	D	D	D	D	D	D	G	G	D	D	D	D
ESC4					F	D	D	D	G	G	G	D	D	D	D	D	D	D	D
ESC5						G	D	D	D	D	G	G	G	G	G	D	D	D	D
GI1							D	G	D	D	D	G	G	G	G	G	G	G	G
GI2								D	D	D	F	D	D	G	D	D	D	G	D
GI3									G	G	G	G	G	G	G	G	G	G	G
GI4										G	S	G	G	G	G	G	G	S	G
GI5											S	G	G	S	S	S	S	G	S
GI6												G	D	G	G	G	G	G	G
D1													S	D	G	D	D	G	D
D2														G	F	G	G	G	G
D3															F	G	G	G	D
D4																F	F	G	F
D5																	F	G	F
D6																		S	F
D7																			D
D8																			

Step 2. Initial reachability matrix (IRM)

The IRM, denoted as (A), illustrates the interconnections among various factors, is determined based on the insights provided by diverse, qualified specialists in their respective fields, and is expressed by the following equations:

$$A = \left(\mathrm{a_{ij}}\right)_{\mathrm{n\times n}} \tag{3}$$

$$\mathrm{a_{ij}} = \begin{cases} 1, \mathrm{V_i M V_j} \\ 0, \ \mathrm{V_i \overline{M} V_j} \end{cases} \tag{4}$$

Here, M represents that V_i is affiliated with V_j, and $\overline{\mathrm{M}}$ means that V_i is not affiliated with V_j. Based on this equation, SSIM is converted into an initial reachability matrix, as shown in Table 4.

Table 4. Reachability matrix (RM).

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Driving power
ESC1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC3	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC4	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC5	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
GI1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	4
GI2	1	1	0	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	7
GI3	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	7
GI4	1	0	1	0	1	1	1	0	1	0	1	0	0	0	0	0	0	1	0	8
GI5	0	0	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	0	1	11
GI6	0	0	1	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	4
D1	0	1	1	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	6
D2	0	1	1	1	0	0	1	0	0	0	1	0	1	0	1	0	0	0	0	7
D3	1	1	0	1	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	6
D4	1	1	0	1	0	0	1	0	0	0	0	0	1	1	1	1	1	0	1	10
D5	1	0	1	1	1	0	1	0	0	0	0	1	0	0	1	1	1	0	1	10
D6	1	0	1	1	1	0	1	0	0	0	0	1	0	0	1	1	1	1	1	11
D7	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	5
D8	1	1	1	1	1	0	1	0	0	0	0	1	0	1	1	1	1	1	1	13
Dependence Power	15	13	15	16	13	5	11	1	1	1	5	5	3	4	7	5	5	4	5	

Step 3. Final reachability matrix (FRM)

The FRM illustrates the straight relationships between various challenges, whereas the reachability matrix represents both direct and indirect connections among factors, denoted by (R). At this phase, the examination of transitivity is conducted to capture circuitous influence within the model. It is achieved using the following equation:

$$A^1 \neq A^2 \neq A^3 \neq \ldots \neq A^\lambda = A^{\lambda+1} = R \qquad (5)$$

Also, λ is adopted to show the sum of computations. Equation 5 illustrates that if a factor i is associated with a factor j, and j is associated with a factor k, then i must be associated with k. Based on this rule, the conversion of IRM into FRM is shown in Table 5.

Table 5. Final reachability matrix (FRM).

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Driving power
ESC1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC3	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC4	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
ESC5	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
GI1	1	1	1*	1	1*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	6
GI2	1	1	1*	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	8
GI3	1	1	1	1	1	1*	1	1	0	0	1*	0	0	0	0	0	0	0	0	9
GI4	1	1*	1	1*	1	1	1	0	1	0	1	0	0	0	0	0	0	1	0	10
GI5	1*	1*	1	1*	1	1	1	0	0	1	1	1*	1*	1	1	1	1	1*	1	17
GI6	1*	1*	1	1*	1*	1	1	0	0	0	1	0	0	0	0	0	0	0	0	8
D1	1*	1	1	1	1*	1*	1	0	0	0	1*	1	1	1*	1*	1*	1*	1*	1*	16
D2	1*	1	1	1	1*	1*	1	0	0	0	1	1*	1	1*	1	1*	1*	1*	1*	16
D3	1	1	1*	1	1*	1*	1*	0	0	0	1*	1	1*	1	1	1*	1*	1*	1*	16
D4	1	1	1*	1	1*	1*	1	0	0	0	1*	1*	1	1	1	1	1	1*	1	16
D5	1	1*	1	1	1	1*	1	0	0	0	1*	1	1*	1*	1	1	1	1*	1	16
D6	1	1*	1	1	1	1*	1	0	0	0	1*	1	1*	1*	1	1	1	1	1	16
D7	1	1*	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	6
D8	1	1	1	1	1	1*	1	0	0	0	1*	1	1*	1	1	1	1	1	1	16
Dep. power	19	19	19	19	19	13	12	1	1	1	12	8	8	8	8	8	8	10	8	

*Transitive links

Step 4. Level partitioning (LP)

The final reachability matrix (FRM) was applied to divide the factors into several levels and find out the hierarchy relations among the variables. The reachability set and antecedent set were computed for every factor using the FRM. The reachability set contains the factor itself as well as the factors that can be impacted by it, and the antecedent set is the set of factors that can impact such a factor. The intersection is the reachability set and the antecedent set of all the above programs. If the reachability and intersection sets for a factor match, that factor is defined at a level. A factor is removed from reconsideration after it is assigned a level. This process is repeated until all factors are allocated levels. According to the results from the level splitting procedure, the hierarchy level of the factors was determined as presented in Table 6. This partitioning involves the RS denoted by $RS(V_i)$, the antecedent set presented as $AS(V_i)$, and the intersection set represented as $\mathrm{IS}(\mathrm{V_i})$; equations are as follows:

$$RS(V_i) = \{V_j | V_j \in V, r_{ij} = 1\} \qquad (6)$$

$$AS(V_i) = \{V_j | V_j \in V, r_{ji} = 1\} \qquad (7)$$

$$IS(V_i) = RS(V_i) \cap AS(V_i) \quad (8)$$

$$L_m = \{V_j | V_j \in V - L_0 - L_1 - \ldots - L_{m-1},\ IS(V_i) = RS(F_i)\} \quad (9)$$

Where L_m shows level m; $m = 1,2,\cdots \lfloor$; $\lfloor \leq n$; $L_0 = \emptyset$.

Table 6. Level partitioning (LP).

Elements (Mi)	Reachability set (RS)	Antecedent set (AS)	Intersection set (IS)	Level (L_m)
1	1, 2, 3, 4, 5,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,	1, 2, 3, 4, 5,	1
2	1, 2, 3, 4, 5,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,	1, 2, 3, 4, 5,	1
3	1, 2, 3, 4, 5,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,	1, 2, 3, 4, 5,	1
4	1, 2, 3, 4, 5,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,	1, 2, 3, 4, 5,	1
5	1, 2, 3, 4, 5,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,	1, 2, 3, 4, 5,	1
6	6,	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19,	6,	2
7	7, 11,	7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19,	7, 11,	3
8	8,	8,	8,	4
9	9,	9,	9,	4
10	10,	10,	10,	5
11	7, 11,	7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19,	7, 11,	3
12	12, 13, 14, 15, 16, 17, 19,	10, 12, 13, 14, 15, 16, 17, 19,	12, 13, 14, 15, 16, 17, 19,	4
13	12, 13, 14, 15, 16, 17, 19,	10, 12, 13, 14, 15, 16, 17, 19,	12, 13, 14, 15, 16, 17, 19,	4
14	12, 13, 14, 15, 16, 17, 19,	10, 12, 13, 14, 15, 16, 17, 19,	12, 13, 14, 15, 16, 17, 19,	4
15	12, 13, 14, 15, 16, 17, 19,	10, 12, 13, 14, 15, 16, 17, 19,	12, 13, 14, 15, 16, 17, 19,	4
16	12, 13, 14, 15, 16, 17, 19,	10, 12, 13, 14, 15, 16, 17, 19,	12, 13, 14, 15, 16, 17, 19,	4
17	12, 13, 14, 15, 16, 17, 19,	10, 12, 13, 14, 15, 16, 17, 19,	12, 13, 14, 15, 16, 17, 19,	4
18	18,	9, 10, 12, 13, 14, 15, 16, 17, 18, 19,	18,	2
19	12, 13, 14, 15, 16, 17, 19,	10, 12, 13, 14, 15, 16, 17, 19,	12, 13, 14, 15, 16, 17, 19,	4

Step 5. Diagram development

Based on the levels extracted from step 4, this step converts different levels into a diagram and places related variables at each level, as shown in Figure 5.

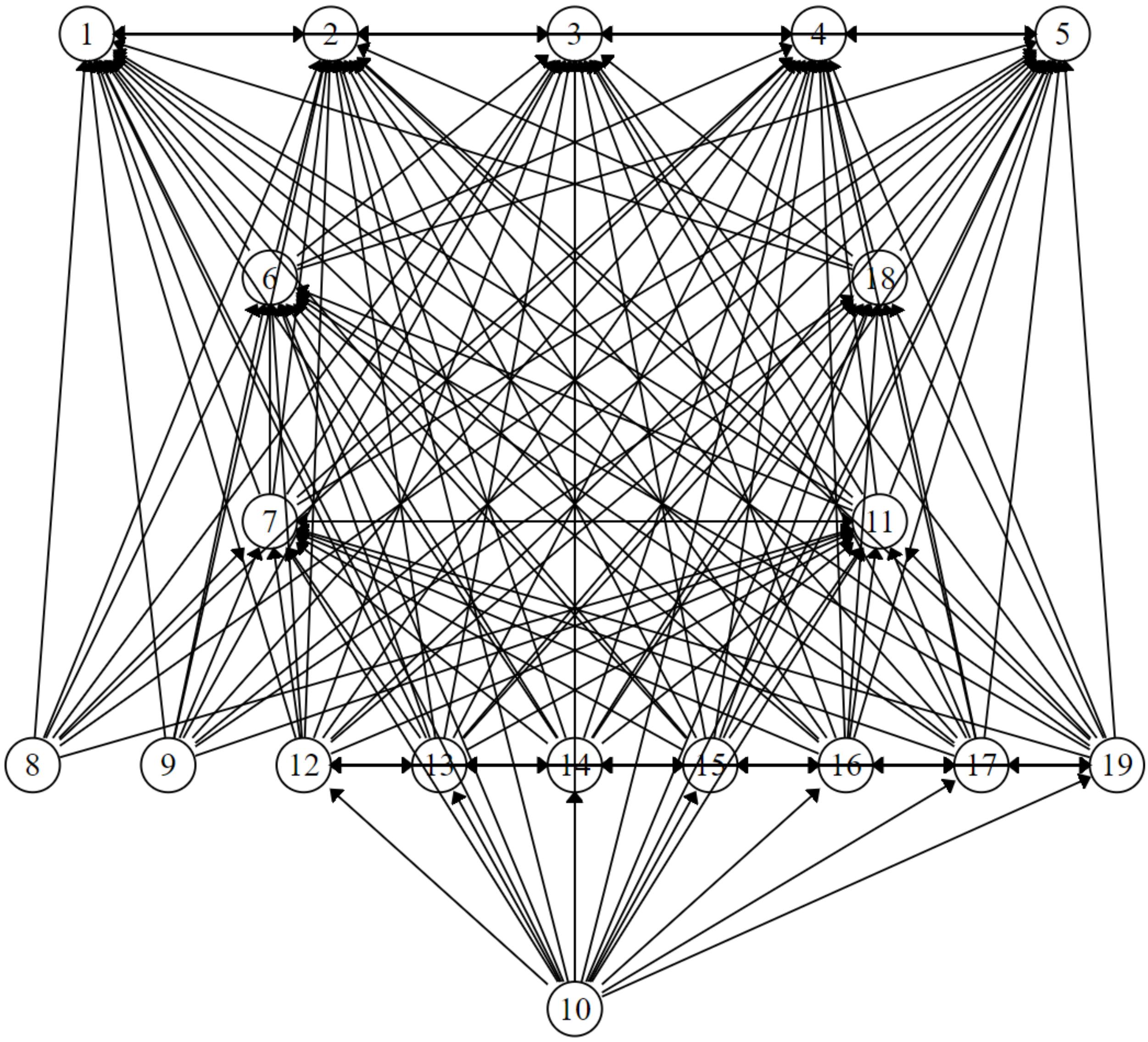

Figure 5. Diagram of the ISM model (Author generated).

Step 6. ISM model

A final model structured by levels is formulated from the outcomes of all iterations and hierarchical levels. The arrows among the factors show the direction of influence, while the arrows point from the influencing factor to the influenced factor. The level assignment is relevant to the degree of influence; factors positioned at higher levels are considered relatively less influential, while those situated at the lower levels are identified as the primary challenges within the system. The final ISM model is shown in Figure 6.

3.7. MICMAC analysis

After establishing the ISM model, the subsequent step involves MICMAC analysis. Duperrin and Godet [25] instituted the MICMAC framework to evaluate the significance of various factors derived from the findings of ISM. A MICMAC diagram is used to position the factors identified in the study on an x- and y-axis, defined as *driving power* and *dependence*, respectively. The driving power is the degree to which a factor acts on other individuals, whereas the dependence is the degree to which a factor is acted on by others. In the diagram, the factors are classified into four clusters, as shown in Figure 7.

The driving factor is denoted as $\mathrm{DF(V_i)}$, while the dependence factor is represented as $\mathrm{DP(V_i)}$, calculated using the following equations:

$$DF(V_i) = \sum_{j=1}^{n} f_{ij} \quad (i = 1,2,\cdots,n) \qquad (10)$$

$$DP(V_i) = \sum_{j=1}^{n} f_{ji} \quad (i = 1,2,\cdots,n) \qquad (11)$$

The description of these clusters is provided below.

3.7.1. Autonomous cluster

This cluster comprises factors with weak driving and dependence power. In this cluster category, factors are separated but demonstrate robust relations with other factors. Even though these variables do not have a strong influence, they are still useful because they can help in specific situations. As shown in Figure 7, none of the variables emerged in this category, which shows that all variables belong in the other three clusters.

3.7.2. Dependent cluster

Clusters displaying high robust power and less dependence are termed dependent clusters. These variables have no influence on the system without the involvement of independent variables. Therefore, if a system has more dependent variables, then there are fewer chances of redundancies. In this system, ten variables emerged in the dependent cluster.

3.7.3. Linkage cluster

This cluster consists of factors possessing significant driving and dependence power, although the factors within this category exhibit instability. Additionally, these linkage cluster factors' impact extends to affect other elements outside this cluster. This dual role implies that any intervention targeting linkage factors must be carefully designed to avoid instability. In this system, one variable (optimization of SC-SCD7) emerged in this category.

3.7.4. Independent clusters

Clusters featuring robust driving and less dependence power exist in the independent category. These are the main driving factors that drive all other factors; they are the most influential variables and should be the primary targets of managerial and policy action, because they have a strong influence on other variables of the system. In this study, nine variables emerged in this category.

Based on the MICMAC analysis, the categorization of different variables is shown in Figure 7.

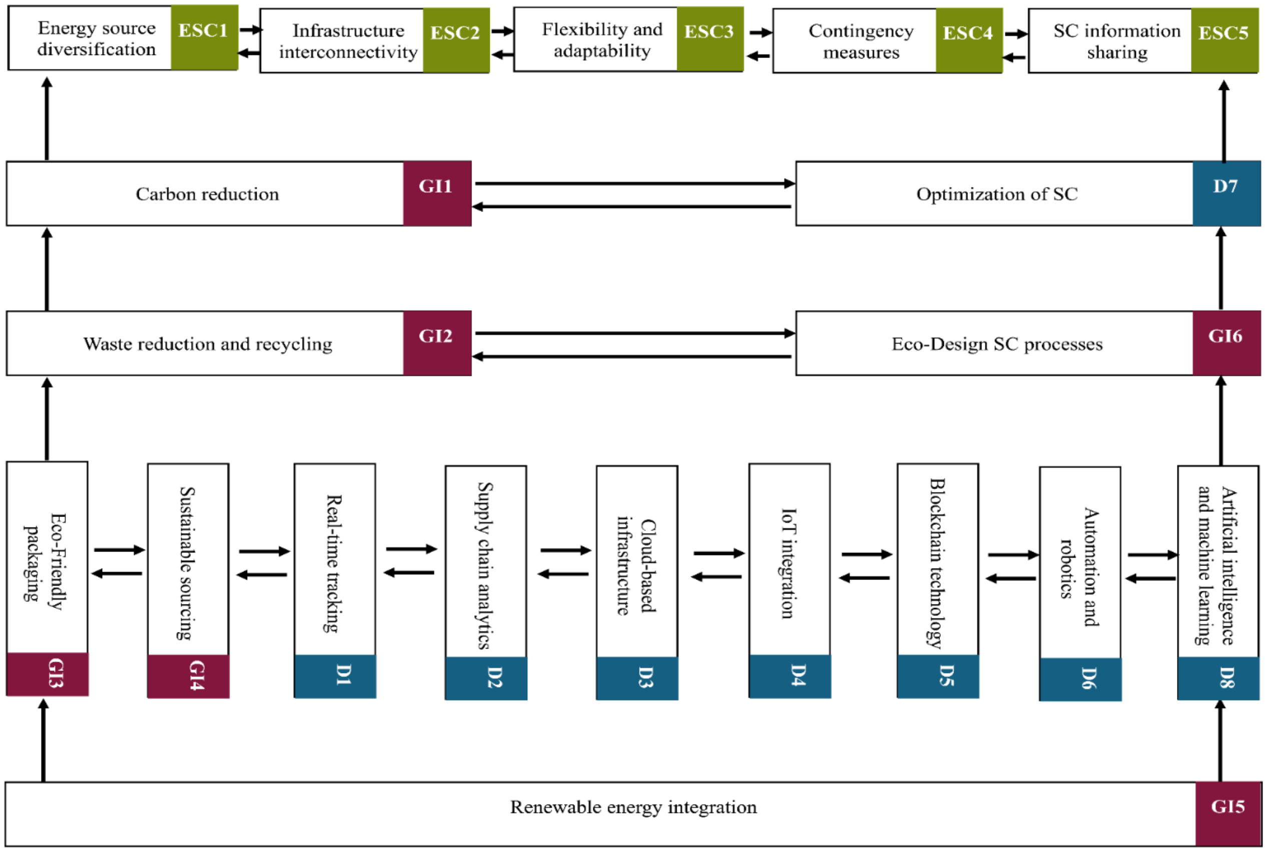

Figure 6. ISM model for the association between digitization, green innovation, and energy supply chain resilience (Author generated).

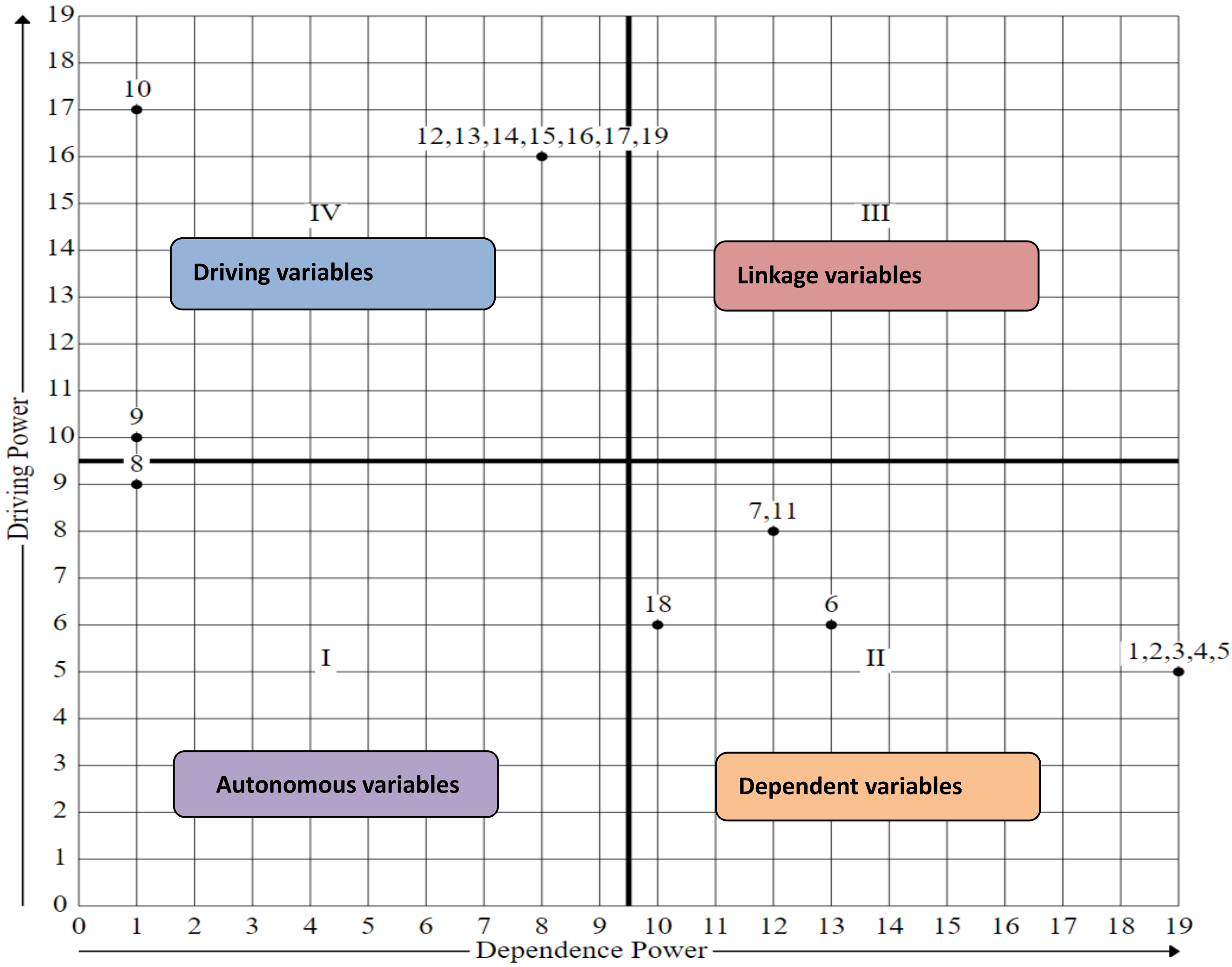

Figure 7. Association between digitization, green innovation, and energy supply chain resilience (Author generated).

4. Results and discussion

The ISM model was used to identify the variables; one was placed at the first level, nine variables at the second level, two variables each at the third and fourth levels, and five variables at the fifth level. At the first level, renewable energy integration (GI5) stands out as the most influential variable affecting ESCR and other factors related to digitization and GI. It aligns with our H1, which highlights that GI has a strong association with ESCR. The integration of renewable energy has significant potential for increasing resiliency in the energy supply chain. Furthermore, diversification would help mitigate the risks of natural disasters or geopolitical crises on energy supply chains, preventing chain disruption and the vulnerability of the energy system. Generation capacity for circuits is provided by renewable energy sources, such as solar, wind, and hydro power, which eases the demand load on the main power grids and enhances energy security [28]. Additionally, the development of energy storage technology has improved intermittent problems in order to convert power into continuous generation. Governments can incentivize this integration by promoting investment in renewables through grants, tax incentives, and benign industry guidelines. Furthermore, promotion of research and development in renewable technologies drives innovation, lowers costs, and helps bring the technology to the market. Both public and private sectors must work together, and so should nations to make sure that the potential of renewable energy sources is fully exploited for a reliable energy future [35].

At level 2, renewable energy integration (GI5) was also found to directly affect seven variables (D1 to D6 and D8), as explained by two specific measures: GI3 and GI4. This reflects the ability to combine renewable energy integration with other disruptive technologies such as IoT, blockchain and cloud-based solutions (D3, D4, D5), AI (D8), and robotics (D6). SCM analytics and tracking/mobility solutions (D1, D2), as well as eco-friendly packaging (GI3) and sustainable sourcing (GI4), collectively create synergies for better ESCR. The findings provide structural evidence consistent with hypothesis H2, indicating that SCD is highly and positively correlated with ESCR. IoT-enabled sensors deployed in renewable infrastructure gather data on how much energy is produced and consumed in real-time, leading to accurate output vs. productivity efficiencies. Blockchain is an emerging technology that provides transparent, secure, and traceable energy trading, enabling real-time integration of renewable energy in the current grid [28]. Artificial intelligence and robotics solutions can boost the performance of renewable energy generation and distribution, make maintenance more efficient, and predict system malfunctions to avoid and mitigate downtime, even when power is not lost [34]. Long-term cooperation among stakeholders and investment in research and development are essential for the integration of renewable energy with these technologies. Governments contribute to the transition by providing tax incentives, subsidies, and regulations that support innovation in renewable energy technologies. Partnerships between energy companies, technology developers (hardware and software), and research institutions can contribute to integrated solutions that leverage IoT, blockchain, AI, and robotics to improve the resilience of the energy system [38]. Moreover, promoting and ensuring transparency around the social and economic benefits of renewables (and environmental stewardship in general) can stimulate further inquiry into the factors that strengthen ties to energy sources, as well as encourage alternative investments in renewable energy [28].

At the third level, IoT, blockchain, AI, robotics, SCM analysis, and traceability (GI3, GI4, D1, D2, D3, D4, D5, D6, and D8) could collectively assist supply chain management by fostering eco-design supply chain processes (GI6) and waste reduction/recycling concepts (GI2). These findings offer structural proof in support of H3, which highlights that the combined effect of SCD and GI produces a stronger ESCR than either construct alone. For instance, in the supply chain, real-time inventory management and monitoring of assets have been made possible thanks to IoT sensors, increasing efficiency levels and reducing waste. The blockchain technology increases transparency and accountability, enhancing the traceability of goods and services, and thereby reducing the risk of fraud and ensuring sustainable sourcing in procurement [36]. On top of that, through AI and robotics, productivity improves by smoothing out and improving precision throughout the entire process, allowing increased production with fewer inputs due to less waste. Furthermore, SCM monitoring and analysis support data-based decision-making, locate improvement opportunities, and facilitate returns logistics, thereby further reducing waste and increasing exposure to sustainable products [37]. Sustainable packaging and material sourcing are employed to help companies lower their environmental impact by reducing waste and improving recycling. In summary, the reduction of waste and promotion of sustainable supply chains not only results in low carbon emissions but also in more efficient and environmentally responsible supply chain efficiency margins [8].

At the fourth level, two important factors (GI1 and D7) of GI and ESCR were identified. The decomposition of these practices (waste reduction/recycling, eco-design) suggests that the carbon reduction (GI1) and optimization of supply chain management (D7) play critical roles. Reducing carbon emissions lessens the dependence on fossil fuels, thereby mitigating risks associated with price volatility and geopolitical instability. A streamlined supply chain enhances agility, enables rapid crisis response, and ensures continuous power. Complementary to each other, these factors intricately enhance resilience, creating a steady supply system amidst shocks and surprises [8].

At the fifth level, carbon reduction (GI1) and optimization of supply chain (D7) were found to be directly related to ESCRs (ESC1, ESC2, ESC3, ESC4, and ESC5). Reducing carbon emissions and improving supply chain performance greatly contribute to improving the resilience of the energy system [33]. By lowering greenhouse gas emissions and using sustainable practices and efficiencies, the manufacturing sector can lessen the effects of adverse weather patterns that can destabilize energy infrastructure. Other benefits are also noteworthy; for example, a productive supply chain can ensure the reliability and cost-effectiveness of energy generation and distribution infrastructure by assisting in logistics, reducing downtime, and providing on-time delivery of materials and equipment. This adaptability is based on a mixture of different energy sources and unconventional technologies to reduce reliance on fossil fuels that harm the environment. In the end, lower greenhouse gas emissions and resilient/economical supply chains result in a robust and scalable energy system that is shock-resistant and can adapt itself to national requirements.

Although the ISM model defines clear hierarchical relationships, its cause-and-effect structure is essentially unidirectional and linear. Indeed, the relationship between SCD, GI, and ESCR is more complex and may involve feedback loops[47]. For example, GI could trigger digital upgrades by introducing smart sensors to monitor emissions. The resulting data feedback could, in turn, help boost the system's resilience in a continuous improvement cycle that the ISM model does not capture. These feedback mechanisms are not included in the ISM model; as such, system dynamics modeling should be further explored. Despite its limitations, the ISM framework serves as a valuable starting place. It helps identify key driving forces and relationships, providing researchers with a clear map for understanding complex connections.

4.1. Theoretical, practical, and managerial implications

The theoretical implications of this study apply far beyond a stakeholder theory's vantage point, namely to a complex web of actors and interests, ultimately impacting energy supply chain resilience. This study elucidates how SCD and GI are significant for organizational resiliency, independence, or response to varied expectations of stakeholders. Through understanding how various stakeholders (e.g., suppliers, customers, regulators, and communities) are interrelated, organizations can ensure that their strategies work in support of broader UN-SDGs while also improving supply chain resilience. Moreover, this study contributes to the literature by clarifying the key role of the manufacturing industry in ESCR formation. Driven by more sustainable ways of decision-making on a macro level, this interest is leading stakeholders to push organizations harder than ever before to adopt more environmentally/socially responsible ways of being and reduce the risk associated with climate change and resource scarcity. Therefore, these results have practical implications for business: an approach to SCM is more likely to be resilient and innovative if stakeholder interests are embedded in strategic action plans and decisions.

The practical contributions of this study are threefold, offering insights to energy industry professionals and policy stakeholders. First, manufacturing companies must make renewable energy an essential priority, as it not only means less carbon emissions but also leads people to further change their behavior. Second, green efforts should be implemented through step-by-step introduction of IoT, blockchain, and AI, in which digital tools must act as green accelerators and not the final goal. This results in a tech leap that reduces costs and increases the effectiveness of the renewable energy transition, also insulating companies from unexpected stressors. Third, governments should introduce selective incentives, such as tax exemptions or reimbursements, to drive sizable effects in specific areas found in our MICMAC study. These implications emerge directly from the interconnection between the ISM model and the MICMAC hierarchy, resulting in specific, data-based suggestions.

This study aims to raise awareness on digitization and green innovation to enhance supply chain resilience. However, managers must deal with many constraints, such as budget and regulatory compliance issues, short lead times, and a balance between cost-efficiency and resiliency. Technologies that require larger investments may, in fact, be less expensive in the long term if they reduce financial losses or disruptions.

5. Conclusion

In conclusion, this study highlights a critical inter-relationship between SCDs, GIs, and resilience in the energy system. Digitization can help organizations streamline processes, improve resource utilization, and better meet the demands of a dynamic market. Furthermore, the incorporation of GI projects not only mitigates environmental harm but also makes the energy supply chain more resilient to stressors such as natural disasters and legislative adjustments. The results of this study suggest that decision-makers should regard SCD and GI investments as priority strategies for strengthening resilience against energy issues. Emerging technologies like IoT, AI, and blockchain are now being used for a real-time overview of the supply chain, allowing the identification of potential risk areas and proactive measures. Second, sustainability practices are not only consistent with UN-SDGs but also associated with increased operational efficiency and improved long-term corporate success. Moving forward, further research and joint efforts among industry stakeholders, policymakers, and academia are necessary to better address the intricate relationships among SCD, GI, and resilience in the energy sector. Working together to share insights and best practices, the various stakeholders in the energy supply chain can meet industry challenges and adapt to changes in order to promote a sustainable and resilient future.

This study has some obvious limitations that should be considered in future research. First, our findings are based on interviews with 15 experts. Despite our intention to capture varied levels of experience, this is still only scratching the industry surface. A more diverse, geographically representative advisory committee should be included in subsequent research. The second limitation pertains to the verification of the Delphi and ISM approaches. Interrater reliability was not computed in the Delphi study due to its site stability (convergence across three rounds). We recognize that this is a limitation and recommend statistical reliability testing in future research. Also, this study did not use another validation process, such as structural equation modeling (SEM), DEMATEL, or robustness sensitivity analysis of the ISM model. Additionally, the hierarchical relationships identified by the ISM model require verification and refinement in the future. Including a sensitivity analysis would also be helpful, as it can demonstrate the stability of the experts' views and the impact of each variable on the model's overall structure. Third, while we delivered a set of product-agnostic supply chain practices, subsequent studies could refine that framework by applying it to a specific domain, such as energy utilities, manufacturing, or logistics, through multi-year case studies. Lastly, this study fell short of conducting a cost–benefit assessment or a detailed examination of trade-offs with the UN-SDGs. Both of these areas remain essential for investigating the effectiveness of supply chains.

Author contributions

Muhammad Ismail: Conceptualization, formal analysis, investigation, Methodology, supervision & project administration, Writing—review and editing; Zhongdong Xiao: Conceptualization, supervision & project administration, Writing—original draft preparation, Writing—review and editing; Abdul Waheed: Conceptualization, formal analysis, supervision & project administration, Writing—original draft preparation, Writing—review and editing; Shahid Mahmood: Conceptualization, investigation; Doaa Sami Khafaa: Conceptualization, resources, supervision & project administration; Amel Ali Alhussan: Conceptualization, resources, Writing—review and editing; El-Sayed M. El-Kenawy: formal analysis, Methodology, Resources, Writing—review and editing; Marwa M. Eid: Investigation, software, Writing—review and editing; Doaa Sami Khafaga: Conceptualization, resources, Supervision & Project administration.

Use of Generative-AI tools declaration

The authors declare that they have not used AI tools in the creation of this article.

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Data availability statement

The data supporting the current study are available within the manuscript.

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Ethical statement

The concerned authorities approved the questionnaire and methodology of the current study. The present study was approved by the Institutional Review Board (IRB) of the School of Business at Xian International University and was conducted in accordance with the Helsinki ethical standards.

Conflicts of interest

There is no conflict of interest among the authors.

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