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Role of industry 4.0 technologies and human-machine interaction for de-carbonization of food supply chains

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A R T I C L E I N F O

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A B S T R A C T

A decarbonized food supply chain ensures that we have access to safe, nutritious, and affordable food with a reduced carbon footprint. It not only helps in reducing greenhouse gas emissions but also enhances food security by making the supply chain more resilient to climate-related disruptions, ensuring stable food production for a growing global population. Further, there is an increasing consumer demand for sustainably produced food, and meeting this demand is crucial for maintaining relevance and competitiveness in the global market. Without a well-functioning decarbonized supply chain, it would be much harder for farmers, processors, distributors, and retailers to promote food security and improve public health. Decarbonization in the food supply chain is a complex process that requires a multifaceted approach, with the entire supply chain from farm to fork being examined. Technological advances such as Industry 4.0, with a human-centric solution, could be an answer. By combining the power of Industry 4.0 with decarbonization efforts, the creation of a more sustainable and efficient food supply chain can be promised. Hence, this study utilizes a mixed-method approach to examine the Indian food supply chain, and analyses the factors that motivate stakeholders to implement decarbonized technologies. It uses opinions from industry as well as from academic experts for employing integrated Analytic hierarchy process (AHP) and Interpretive structural modelling (ISM). AHP revealed that "International community pressure" is the most critical factor. Further, ISM is used to explain the interrelationships among the identified factors, providing a hierarchical model. These key findings can assist policymakers to develop and refine regulations. Further, it can also help stakeholders to make an informed decision while allocating resources towards new technologies.

1. Introduction

The phrase 'food system' means a diverse set of food-related activities, including food production, processing, and packaging, alternative forms of food production, food distribution, marketing and value chains, data and analytics, addressing waste, use of energy and water, and procuring affordable food (NASEM, 2020). All through history, human beings have tamed native plants and animals to serve their personal needs, leading to an abundance of food. In addition, over time there have been numerous innovations in agriculture, enabling human beings to produce more food to meet the needs of a growing population (Sroufe and Watts, 2022). The premise of this study is grounded in the staggering percentage of carbon emissions arising from the food system and underpinning the journey from farm to fork. For example, agriculture in India, entire food supply chain uses approximately 200 PJ of energy annually (Ladha-Sabur et al., 2019), and it exceeds the energy requirements of the US and of China (Sovacool et al., 2021). Poore and Nemecek (2018) calculated that farming activities, including the felling of trees, are responsible for 81% of emissions.

Therefore, focusing on the decarbonization of the food supply chain is imperative for minimizing the discharge of dangerous gases, reducing the consequences of climate change, and attaining the objective of sustainability (SCD, 2023). Decarbonization is the method of minimizing the carbon footprint or carbon dioxide (CO_2) emissions

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generated by different processes, industries, or societies, with the basic aim of mitigating climate change. Zhou et al. (2024) consider this to be a real-world concern of our global ecosystem and not merely a conceptual dilemma.

With a focus on the decarbonization of agri-food and supply chains, the report of the UNEP (2019) highlighted the need to implement a multi-disciplinary strategy to attenuate harmful emissions and meet the aggressive aim of a 7.6% reduction of greenhouse gases (GHG) per year from 2020 to 2030 (Adelodun et al., 2021). In addition, the authors posited that food waste is a hotspot for carbon emissions, and that addressing this can accelerate the minimizing of emissions and the accomplishment of decarbonization in the agri-food sector (Cakar et al., 2020; NASEM, 2020). Since 1990, according to the European Environment Agency (EEA) report (2023), there has been a drop of a third in the cumulative GHG emissions in the EU, but minimizing emissions in the agro sector has been a slow-moving endeavour that has come to a standstill since 2005. The report further states that, under the current policies of the EU countries, it is anticipated that this pattern will continue with a 1.5% decrease from 2020 to 2040. On implementing waste reduction and reuse initiatives, a net saving of 600 billion EUR is estimated for industries in the EU (Kalmykova et al., 2018).

The USDA (2021) claimed that, ironically, regardless of the agricultural industry's attempts to escalate efficient production, food in the developed economy of the US on average travels 1400 miles before reaching US citizens' tables, and an exorbitant proportion of this food, around 40%, goes to waste. In another recent investigation into the developing economy of India, Sharma et al. (2023) proposed a framework for fresh food supply chains (FFSC) that focuses on creating resilient and sustainable supply chains. However, their research discussed four fundamentals of sustainability and did not address the reduction of carbon emissions at the grassroots level in totality. This investigation takes a more comprehensive approach by identifying twenty-seven drivers, and addresses the critical catalysts (international community pressure, regulatory requirements, government support, and stakeholder pressure) for decarbonization in the Indian food supply chain. To the best of our knowledge, there has been no empirical investigation related to decarbonization in the Indian food supply chain that covers all sectors from farm to fork and evaluates multiple constructs, and this adds to the robustness of this investigation.

India must integrate rapid measures of decarbonization, considering its vast population of 1.42 billion (News 18, 2023), and the current situation is worrying for the literate cohort and the environmentally-sensitive population of India. This vast population is susceptible to the detrimental impact of climatic variations, with transitions in rain patterns having impacts on agriculture, which translates into uncertainty of crops and soaring prices for basic food products. Decarbonization measures can give tenacity to food supply chains by making them flexible to climatic imbalances and ensuring food security. Secondly, as most emissions come from food supply chains, if industries in India integrate initiatives to decarbonize their supply chains, India can make a strong contribution to the global attempts to reduce carbon emissions by exemplifying adherence to ecological stewardship. Therefore, it is imperative that India embraces efficient techniques to ensure decarbonization in agro supply chains and simultaneously educates its population about the many merits of doing this.

The first step is investment in research and the inclusion of Industry 4.0 smart technologies for a sustainable future that are efficient in facilitating decarbonization (Kumar et al., 2022b; Mishra et al., 2023). These technologies should be accessible to urban as well as rural societies. In addition, there must be forums and awareness drives to educate people about the relevance of environmental conservation and the benefits and impacts for people of a healthy and clean environment. Enhancing a 'clean and green' awareness among consumers is a critical market-driven construct for achieving a sustainable supply chain (Li et al., 2021). Levying taxes and/or enforcing strict regulations and/or offering subsidies to industries generating harmful waste to enable them to reform their processes could be the second step. Industries must take responsibility for their endeavours and must dispose of the waste they generate in a secure and responsible way. The government authorities must also motivate the implementation of the three Rs (reduce, reuse, and recycle) (Vlajic et al., 2021), besides encouraging the use of natural energy resources like solar power (Yu et al., 2021) to curtail atmospheric pollutants. For residents living in proximity to industries, this step can have a notable influence on their health. This is the time for policymakers to hasten awareness among populations and ensure a safer and healthier future for the next generations.

With this background, the amalgamation of the triple bottom line (TBL) and digitalization in the context of Indian food supply chains is the unique aspect of this investigation. This is the first empirical investigation to examine Indian food supply chains and to interpret the linkages between decarbonization, Industry 4.0, sustainability, and twenty-seven food supply chain drivers. The analytic hierarchy process (AHP) and interpretive structural modelling (ISM) are adopted to achieve greater clarity in the findings. These methods provide a useful way of investigating the complex associations among all the constructs considered in this study. The strength of this analysis is the dissemination of the relationships among the variables that steer food supply chains towards achieving decarbonization and, thereby, sustainability.

The following research questions are formulated based on the above discussion:

RQ1: What frameworks are appropriate for understanding food supply chains in India?
RQ2: What pertinent components/constructs motivate a firm to move towards decarbonization?
RQ3. What is the hierarchy of the identified components/constructs?

The results indicate that international community pressure, regulatory requirements, government support, and stakeholder pressure are the major drivers for decarbonization in the Indian food supply chain. This study uses ISM to highlight how the relationship among the constructs can be used to attain sustainability from food production to distribution.

The remaining sections of this paper are organized as follows. Section 2 covers the constructs in the various approaches used to achieve decarbonization, with a detailed literature review and analysis. Section 3 explains the research methodology and the rationale for using AHP and ISM. Section 4 indicates the results with a summary of the findings (Subsection 4.1), and explains the relative positions of the identified constructs in attaining decarbonization (Subsection 4.2). Finally, Section 5 presents a discussion and Section 6 presents the implications, while the conclusions, limitations, and future research directions are presented in Section 7.

2. Literature review

2.1. Theoretical background

Technological transformations and innovations in firms and their supply chains (SCs) are strongly influenced by the technological, organizational and environmental (TOE) context according to what is popularly known as the TOE framework (Tornatzky and Fleischer, 1990). Various researchers have adopted the TOE framework to understand the technological changes and innovation that have taken place in different industries, including the pharmaceutical industry (Graham, 2024), food (Nilsson et al., 2021), and construction (Wu et al., 2023). The technological context considers the existing technologies in a firm that are important in determining the ability of the firm to evolve and adapt to changes. The organizational context considers resources, communication channels and firm size, while the environmental context considers the regulatory environment, service providers and the competition. However, to make innovations sustainable and carbon-free, an understanding of the three important pillars of the social, environmental and economic aspects is also required. With enhanced innovation, products have become complex and difficult to recycle (Galbreth et al., 2013). Thus, innovative tools and techniques to ensure long-term sustainability have enable SCs to combine digital solutions that take into account environmental impacts. Lichtenthaler (2021) used the term 'digitainability', which focuses on the combined effect of digitalization and sustainability; here, digitalization focuses on creating accessible and scalable digital platforms. The author claimed that these megatrends attempt to bring about a more effective, efficient and low-carbon environment for the benefit of people and the planet, while also ensuring profitability across supply chains. Organizations may follow only digitalization initiatives, or only sustainability initiatives, or both, as the needs of the supply chain override the focus. Digitalization and sustainability play a crucial role in business transformations (Gupta et al., 2023). The power of digitalization can be used to move towards sustainability by directing the correct interventions and leveraging the positive aspects of the use of technologies such as artificial intelligence (AI) and machine learning (ML) to create transparency and agility in the system. Although more has to be done to understand the impacts and challenges of going digital, these interventions have to be identified in studies to ensure a better environment for organizations. The synergy between interdisciplinary team skills, sustainability, and digitalization signals a new era of industrial innovation with sustainability as the backbone (Luthra et al., 2020; Mangla et al., 2024). By fostering collaboration, embracing sustainable practices, and leveraging digital technologies, organizations can realize the full potential of Industry 4.0 while advancing environmental stewardship and societal well-being (Kumar et al., 2023; Luthra et al., 2021).

2.2. Decarbonization in the food supply chain: a boon

Population explosion and the need to meet increasing demands, together with changing dietary patterns, underscore the GHG emissions emanating from the food supply chain (FSC) (Grosso et al., 2020). Food emits one third of global GHG emissions (Wang et al., 2022), with 27% being emitted during the crop production phase and 18% during supply chain activities (Poore and Nemecek, 2018). Moreover, global sourcing, production and distribution make the FSC complex and one of the toughest to decarbonize. Thus, sustainable food production and supply chain practices, along with the close monitoring and control of carbon emissions along the FSC, become pivotal to combat the increases in GHG emissions. Decarbonization in a FSC refers to the elimination of carbonaceous depositions and the creation of carbon sinks, together with the reduction of energy-intensive practices in transportation, production, and processing. However, it is important to recognize that reducing energy-intensive practices requires the adoption of clean and green energy technologies, energy-efficient buildings, and the green Internet of Things (IoT), which together are popularly termed decarbonization technologies (DTs). However, to exploit the benefits of DTs and make quick and effective decisions, it is essential to embrace solutions based on Industry 4.0 (I4.0). These advanced technologies ensure the optimal use of resources to effectively reduce carbon emissions, thereby contributing to a sustainable future (Kumar et al., 2022). It is also critical for economies to match the growth of decarbonization with digitalization to avoid a high-carbon environment (Fouquet and Hippe, 2022).

2.3. Drivers of decarbonization in supply chains

I4.0 plays a fundamental role in the evolution of smart SCs (Sharma et al., 2020) as it provides an excellent opportunity to simplify decision-making, select carbon-efficient methods and adaptable practices, and conveniently monitor and regulate carbon emissions. Xu et al. (2023a) emphasized that DT and I4.0 technologies are the key drivers in lowering carbon emissions. The authors also affirmed that DTs require intelligence from I4.0 in order to analyse cost-effective solutions for production that have the least energy consumption. One of these solutions is the green IoT, which has been successful in reducing carbon footprints by replacing energy-intensive activities with green sensing and green tags. Green tags are certificates that are tradable and intangible and specify that the owner has used energy from renewable sources (Hansen et al., 2022). Aliahmadi et al. (2022) presented a framework for steel manufacturing to pave the way for the implementation of green SCs through technological applications. Innovative solutions like low-carbon packaging and green sensors are necessary initiatives in the agri-food sector. Likewise, the accurate measurement of carbon data requires the application of digital technologies with continuous monitoring capability (Pearson et al., 2023). Spanaki et al. (2022) discussed disruptive technologies in agriculture such as AI-driven decision-making that can create a smart environment for agriculturalists. Unless and until measurement and reporting are defined, there will be questions about the actual control of GHG emissions (Kumar et al., 2023a). The selection of the right technologies must therefore be made by each SC partner by developing a shared understanding of emissions. This could be supported by co-designing a hybridized framework considering the whole SC to tackle the climate change problem. By embracing this advance, companies across geographies could make substantial progress towards creating a low-carbon environment.

Enterprises with a greater scope of business are more likely to invest in innovative technologies that reduce carbon emissions (Khan et al., 2021). Sovacool et al. (2021) presented an exhaustive list of the socio-technical aspects of decarbonization covering nine categories of energy-intensive activities in food like chilling and freezing, heat processing, mixing, material preparation, post-processing operations, and utility processes in the food. To create and sustain a low-carbon economy, leadership and talent also need to be blended, which could be operationalized through top management support (TMS) (Moreno-Camacho et al., 2023). Employees need to be trained for the proper implementation of decarbonization technologies by creating a collaborative environment. It is also obligatory to make certain tactical decisions in network design, lean practices, and the use of low-carbon logistics (LCL), as these significantly reduce carbon emissions. Similarly, reverse logistics (RL), which focuses on returned products, reduces carbon footprints through green and lean practices, ensuring the greening of the ecosystem through optimized processes and utilization of materials (Marić and Opazo-Basáez, 2019). Investing in carbon-efficient energy systems and using low-carbon resources helps achieve carbon efficiency in the supply chain (Lim et al., 2020). To achieve CEff throughout an SC it is instrumental to share data and motivate SC partners in co-decision-making (Xu et al., 2023a).

The dietary patterns of consumers creates demand for products which require energy-intensive processes. Veeramani et al. (2017) claimed that there was an increasing requirement for energy for the processing and preservation of meat products. Therefore, low-carbon diets and meat alternatives will reduce the energy requirements in the agri-food sector tremendously (Sovacool et al., 2021). In this direction, Nguyen et al. (2019) posited that stakeholders need to be motivated and educated about the advantages of consuming and producing a low-carbon diet. Such environmental consciousness (EC) among consumers and producers could be a win–win strategy for climate experts and agriculturalists. Interdisciplinary team skills (ITS), which can be gained through training and certification, will enhance the capability of individuals to assess the low-carbon operations and services. These skills are crucial for motivating and creating awareness among employees, and designing innovative solutions (Arundel et al., 2019).

The social dimension of sustainability focuses on the well-being of the community (Lemos et al., 2022). Sovacool et al. (2021) and Lovarelli et al. (2020) claimed that decarbonization ensures healthy working conditions as it reduces pollutants and waste during food processing operations. Wan et al. (2020) set out the requirements for social integrity (SoI) in all practices, especially corporate social responsibility (CSR) practices in SCs. The transparency achievable through technology, together with encrypted and digitally immutable data, has become a boon for governments wanting to track supply chain management (SCM) processes and ensure SoI. CSR activities are initiated and influenced by various economic, cultural, and institutional factors (Dmytriyev et al., 2021). They help in creating a brand image and hence in collaboration opportunities for businesses. Fortunati et al. (2020) very clearly emphasized the role of CSR in identifying and implementing low-carbon solutions in SCs. Moreover, the human-centric approach has become a front-runner during the design and development of products and services (Chen et al., 2021) that are essential to meet the needs of both customers and employees (Labanca et al., 2020).

Studies such as those of Parra et al. (2019) and Adelodun et al. (2021) have claimed that the advantage of adopting low-carbon strategies in SCs is that it creates a more eco-friendly environment with long-term economic benefits. Acampora et al. (2023) suggested that the agri-food industry could benefit from free certifications, subsidies, and borrowing options to support lower carbon emissions. Additionally, incorporating organizational practices like reverse logistics can significantly reduce redundant practices and ultimately cut costs, as suggested by Chen et al. (2019). However, Mayhew (2016) and Shukla et al. (2023) highlighted that the agri-food sector also acts as a carbon sink due to its unique capability of absorbing emissions on land, which is challenging for other sectors.

Studies have emphasized that environmental forces such as international community pressure (Damoah et al., 2021; Huang and Xiao, 2023), external stakeholders (Diniz et al., 2021), and government support (Lim et al., 2020) play an important role in enforcing the reduction of carbon emissions across the world. Some of the global agencies that regularly update country-specific emission standards are the Environmental Protection Agency (EPA) in the United States, the Central Pollution Control Board (CPCB) in India, the European Environment Agency (EEA) in Europe and the Ministry of Ecology and Environment (MEE) in China. These external bodies provide timely guidelines to their respective economies and align their emission strategies with global standards. They also ensure the timely measurement and control of carbon emissions, ultimately reducing global warming. According to Khan et al. (2021) national and international boards set regulatory requirements for international trade. They also promote market strategies such as carbon taxes, the eco-labelling of products, and green supply chain management practices to regulate carbon emissions. The most attractive of these strategies are carbon taxes, which force trade partners to pay a price for the carbon they emit, thus motivating them to use green technology to ensure sustainable business practices. Thus, external forces play a vital role in controlling carbon emissions locally and also globally.

2.4. Analysis of literature and research gaps

Studies in decarbonization are predominantly from countries like China and the US and mainly cover manufacturing industries (Kumar et al., 2023b). The majority of these studies discuss the cost implications of the transition to low-carbon business operations (Tvinnereim and Mehling, 2018) and future growth. In developed nations, the majority of studies are in the shipping sector (Irena et al., 2021) and the energy sector (oil and gas) (Romano and Yang, 2021). The Indian FSC, which continues to face multiple challenges such as changing climatic conditions, natural disasters, and changing dietary requirements of customers belonging to diverse cultures, has received less attention. Infrastructure issues also impose tremendous pressure on decision-makers wanting to design low-carbon strategies in the Indian subcontinent. Decision-makers are also perturbed about ways to reduce GHG emissions, as DT requires huge investment in the short run despite providing long-term economic growth. As food travels, agricultural and land practices (production including harvesting), cleaning, processing, logistics operations (warehousing and transportation) and finally end customer fulfilment processes including the activities of retail stores, all add to the carbon emissions. Because the carbon footprint increases with the food miles, the right collaborative strategies among all the actors in the FSC and the reduction of intermediaries could create a unified approach towards combating the problem (Acampora et al., 2023). Such collaborative strategies require the adoption of DT for the transition of the current FSC to a smart, intelligent and sustainable one, which is popularly termed a 'Greentelligent' SC (Kumar et al., 2023; Pearson et al., 2023). Although many authors have regularly advocated and emphasized the need for a carbon-neutral ecosystem in different Indian industries, the Indian food sector has taken a back seat.

Among the handful of Indian studies on decarbonization, the practices discussed are specific to particular SC stages. This implies that there is still a need for holistic investigations of the farm-to-fork model and the control of carbon emissions along the chain. Also, as developed economies emphasize the role of technology in successfully designing decarbonized supply chains, studies on the Indian FSC could benefit from the same ideas. Thus, identifying the leading factors in carbon reduction in the FSC is a prominent need in the sector. There is a lack of a framework that could guide the FSC towards resolving the issue of resource crunch and dealing with the high cost of technological applications in order to make a 'Greentelligent' SC. Nayeri et al. (2023a) posited that I4.0 could play a role in bringing responsiveness to an SC. A wide role for I4.0 and information and communications technology (ICT) was emphasized in the study by Zang et al. (2023). For the pharmaceutical industry, Rekabi et al. (2023) presented some cost-effective models for creating a smarter supply chain. The study by Neto et al. (2023) very specifically addressed the scenario of the agricultural supply chain and reported differences in opinion and the adoption of digital technologies in activities upstream and downstream. Lee et al. (2023) also discussed green finance in decarbonization in the Chinese context. Several frameworks have been discussed and developed for studying and implementing decarbonization practices globally. To understand the factors that help decarbonization through digitalization, it is important to use a well-tested empirical framework. According to Baker (2012), the adoption of any innovation involves aspects such as technology, organization, and environment (TOE). When an organization wants to make a revolutionary paradigm shift, such as decarbonizing the FSC, all the pillars of technology, organization, and environment must be well aligned. One study that adopted such a framework is that of Nilsson et al. (2021), which considered decarbonization practices in manufacturing and the agri-food sector using a TOE framework. For SMEs, Abed (2020) adopted a similar framework to establish the factors influencing the adoption of social media. This framework requires an understanding of the technological and organizational readiness of firms to adopt a new technology or process improvement. An understanding of the impact of the external environment on the adoption process is also a pre-requisite, contemplating resource availability and the infrastructure support that will boost adoption. Thus, for a transition to a decarbonized FSC, businesses need to understand the TOE framework. Nevertheless, to make any transition a sustainable one, supply chains need to adopt sustainability pillars, which may be social, economic, and environmental. The reason is that, as resource depletion happens at an exponential rate in developing countries, feeding the increasing population becomes challenging. Nonetheless, a major portion of the food that is produced goes to waste and is unaccounted for in developing nations.

The scarcity of studies exploring the propagation of relationships among the decision variables in FSCs for achieving carbon reduction will influence decision-making. Research conducted by Sharma et al. (2022a) explored the intricacies of managing the supply chain for perishable goods, and provides valuable insights for the manufacturing industry. As food products face particular challenges, if a quick fix to various issues is unaddressed, this can have a domino effect in the FSC. Therefore, digitalization and its role in decarbonizing the FSC, with an understanding of both the positives and the negatives, should be thoroughly examined. A holistic transformation strategy that identifies low-cost carbon practices in the FSC in order to achieve a decarbonized FSC (DFSC) is a great opportunity to achieve long-term economic growth.

Empirical evidence about the linkages between the variables in the FSC is missing. Consequently, the present study explores the plethora of variables that can work in favour of achieving a DFSC, by integrating TOE with personal factors and the triple bottom line.

3. Research methodology

A mixed methodology was used to tackle this problem in the domain of the FSC. Fig. 1 sets out the seamless methodology followed in the study. The first phase of the study involved a qualitative approach, with a thorough analysis of the literature to conceptualize the problem context. This qualitative phase was the most crucial part of the paper and laid the foundation for the other two stages. The three research questions that emerged from the critical analysis of the literature led to the three approaches in the study. The first phase attempted to answer the first research question, and led to the analysis and categorization of the relevant farm-to-fork variables that are indispensable to the decarbonization of the whole gamut of the FSC. In this phase, the variables identified were verified from the literature and through several rounds of interviews with ten experts from both academia and industry. The factors influencing decarbonization in the context of the Indian FSC were confirmed, and few new variables were identified. In this stage the variables were carefully categorized into the six dimensions of Technology, Organization, Personal, Social, Environmental and Economic (abbreviated using the acronym TOPSEE). Table 1 displays the outcome of the qualitative phase that addresses the first research question.

The second phase used the input from the first phase and involved the application of two popular multi-criterion decision-making (MCDM) techniques: AHP and ISM. AHP was used to solve the second research question and ISM for the third research question. These two MCDM techniques are very popular in solving similar problems when there is a requirement to rank and develop the relationship between multiple variables. Past studies have also used the AHP approach for ranking and prioritizing variables and have then applied the second method to determine the relationships. The two methods are well accepted among the research community, as found in studies such as those by Kumar et al. (2023), Sharma et al. (2023d), Prabhakar et al. (2021) and Yadav and Samuel (2022).

AHP was used to rank the identified factors to explore their criticality in the Indian FSC. In the AHP methodology, a pair-wise matrix is first used to calculate the criteria using a Saaty Scale. The consistency ratio (CR) was determined using the ratio of the consistency index (CI) and the random consistency index (RI). The method is detailed in Supplementary file S3.1.

In the next step, ISM was used to explore the hierarchy among the variables of concern and to identify the driving factors. ISM is a useful way of investigating the complex associations among all the constructs considered in this study. The strength of this analysis is the dissemination of the relationships among the variables that can steer the FSC towards achieving decarbonization and, thereby, sustainability. The development of this unidirectional model consists of structural relationship identification, clustering and validation. These steps in the ISM methodology are detailed in Supplementary file S3.2.

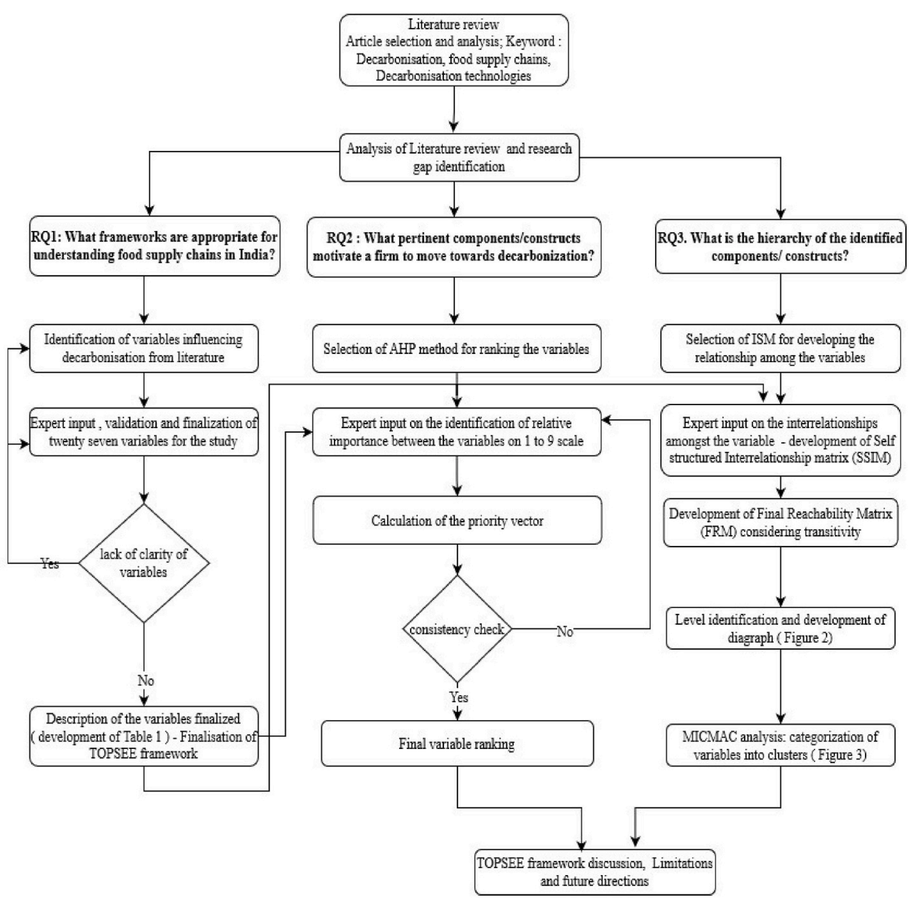

Fig. 1. Research methodology adopted in the study.

Table 1
Definitions of variables used in TOPSEE framework.

Dimension	Variable	Definition	Role of variable in decarbonization	Authors	Context/Country
Technological (T)	Decarbonization technology (DT)	Reduction of carbon emissions using fuel vehicle technologies, and energy-efficient buildings. Other techniques involve carbon capture, utilization, and storage (CCUS) technology, green tags and packaging design initiatives.	Green tags and sensors are green IT software and hardware solutions. These reduce the unnecessary usage of energy by involving occupancy sensors.	Xu et al. (2023b); Kumar et al. (2022)	Supply chain/US, India, China
	Industry 4.0 technologies (I4.0)	The digital, physical, and biological technologies in the fourth industrial revolution (AI and ML-driven technologies, IoT, cloud computing technology (CCT) and additive manufacturing (AM) technology such as 3D printing).	IoT systems can facilitate monitoring and management in the food industry and secure the quality of food. The IoT allows intelligent vehicle routing and tracing sources of contamination in food	Khan et al. (2021); Hansen et al. (2022); Nagarajan et al. (2022)	Food sector/ China, Pakistan
Organizational (O)	Optimized networks (ON)	Cost-effective transportation networks that enhance transportation efficiency.	An optimized network identifies redundant moves to reduce carbon emissions.	Bozdoğan et al. (2023)	Global supply chain
	Employee training (ET)	Creating awareness among employees through regular training regarding sustainable practices and carbon reduction in all the operational activities of the supply chain.	These practices motivate employees to keep a continuous check on carbon emissions and their root causes.	Xu et al. (2023a); Lin et al. (2023)	Alumina industry/ China
	Top management support (TMS)	Support of top management in organization's activities.	Top management supports, directs, motivates and fosters an environment so that a firm's green and lean practices reduce GHG emissions.	Moreno-Camacho et al. (2023)	Dairy sector/ Columbia
	Reverse logistics (RL)	Activities involving recycling, reusing and/or remanufacturing returned products or material waste for re-production.	Reverse logistics reduces waste and ensures the recycling of produce and packaging materials.	Chen et al. (2019)	Retail industry/ General
	Lean practices (LP)	Firms' practices regarding reducing waste by following lean practices. These include practices such as Six Sigma, continuous improvement, 5S of housekeeping, TQM, VSM and TPM.	Lean practices reduce waste and this has a potential impact on carbon emissions.	Negrão et al. (2017)	Manufacturing/ General
	Low-carbon logistics (LCL)	Firms' capability to switch to alternative modes of transport and consolidated movements such as platooning for low-carbon logistics.	Firms' decisions regarding shifts in modes of transportation or, for example, carpooling aids in keeping carbon emissions low.	Wang et al. (2022)	Logistics operations/None
	Carbon efficiency capability (CEff)	Producing output with minimum carbon emissions in SC activities.	Integrating various technologies to improve the overall carbon efficiency in the supply chain and hence achieve a decarbonized supply chain.	Lim et al. (2020)	Logistics industry/ China
	System integration (SysI)	Integration of different interfaces and information systems in the supply chain.	Identification of optimal resource utilization is possible through integrated systems, as actual supply and demand patterns can be captured in real time.	Sharma et al. (2023)	Logistics industry/ China
	Data sharing (DS)	The transparent, efficient and safe sharing of data points regarding sales, inventory, resource utilization, performance measures between SCM members and other stakeholders for making smart decisions.	Sharing of data pertaining to the carbon footprint of resources tremendously cuts its utilization along supply chains.	Xu et al. (2023b)	General supply chain/None
	Supply chain collaboration (SCC)	Vertical and horizontal integration among the supply chain partners.	Collaboration among players paves a path for encouraging partners to follow low-carbon supply chain practices.	Watabe and Yamabe-Ledoux (2023).	General/Japan
	Low-carbon sourcing and production (LCSP)	Integrating low-carbon technologies with Industry 4.0 technologies or other SCM processes for fewer carbon emissions during production/sourcing.	This has a significant impact on the overall carbon footprint of food supply chains as the chances of emissions are directly tackled at the source itself.	Yao et al. (2021)	Power sector/ China
Personal (P)	Environmental consciousness (EC)	Behavioural change at the point of use. Use/disposal of product and/or service in a more environmentally aware manner.	Consumers can be motivated to follow a low-carbon diet which will ultimately reduce the consumption and thus the demand for products with high carbon footprints.	Mehta and Chahal (2021)	Automobile industry/India
	Interdisciplinary team skills (ITS)	Staff attributes can provide flexibility and agility in order to address unsatisfied customer needs: initiative, open-mindedness and ability to work in interdisciplinary teams	Interdisciplinary team skills will encourage employees to use the customized tools and equipment such as decarbonized technologies and solutions such as renewable energy. Jobs in such streams are called green jobs. These technologies require team skills to be developed among employees.	Xu et al. (2023a)	Supply chain/ General

(*continued on next page*)

Table 1 (*continued*)

Dimension	Variable	Definition	Role of variable in decarbonization	Authors	Context/Country
Social (S)	Job creation (JC)	Creating job opportunities such as green jobs. Green jobs refer to work in renewable energy sources that require specific knowledge and skills.	The introduction of technologies will create jobs and education opportunities, helping SCM development and improving supply chain sustainability.	Singh and Shabani (2016)	Food supply chain/India
	Health and safety (HSf)	Protecting people's health and shielding them from risks, harm, and dangers is essential to creating a safe and secure environment.	With the help of technology, services and products can be provided to people in need, contributing to societal development. This variable fosters an environment for individuals to promote and practise decarbonized technologies.	Damoah et al. (2021)	Healthcare industry/Ghana
	Governmental support (GS)	Support and incentives provided by governments.	This support increases the willingness and performance of organizations towards low carbon emissions.	Lim et al. (2020)	Energy sector/ None
	Social integrity (SoI)	The trustworthiness of the SC partners makes sharing of the data unmodifiable.	Ethical practices ensure the correct utilization of time and effort to make the right decisions about reducing carbon emissions.	Johns et al. (2013)	Manufacturing/US and Europe
	Human centricity (HC)	All the design and development of products, services and processes has a human emphasis.	More customizable equipment helps workers to understand and make effective decisions.	Sharma et al. (2022c)	Pharmaceutical sector/India
	Corporate social responsibility (CSR)	Activities related to CSR at the focal and the supply chain level.	CSR activities help to promote a culture and practices of individuals, organizations and partners directed towards low carbon footprints.	Zhou et al. (2024)	General supply chains/China
Economic (E)	Economic growth (EG)	Generally greater prosperity, better living standards, higher earnings, and more job opportunities in the country due to improved products and services.	The decarbonization approaches and technology used can influence firms' income and market status, and reduce their emissions, leading to lower carbon taxes. Technological advancement and skilled workforce are essential for economic growth.	Liao et al. (2017)	Energy sector/ Poland
	Reduced supply chain cost (RC)	Selection of the right decarbonized technologies using intelligent decision-making can reduce the costs of production and other SCM processes.	Lower usage means fewer carbon emissions in the environment.	Kaur and Singh (2018)	Logistics activities/India
Environmental (E)	International community pressure (ICP)	International boards create awareness and protocols that call for action and cooperation in the face of climate change and global warming.	Awareness among the global community also forces countries to mutually agree to ensure that businesses comply with good environmental practices.	Huang (2022)	Developed and developing countries
	Stakeholder pressure (SP)	Low-carbon opportunities or requirements from supply chain stakeholders.	Awareness among stakeholders of the impact of their carbon footprint on their organizations motivates them to partner with players concerned about the environment.	Diniz et al. (2021)	Energy sector/ Brazil
	Regulatory requirements (RR)	The environmental standards, rules, and laws proposed by the authorities.	The rules and protocols lay a foundation for the enforcement of organizations to conduct low-carbon practices.	Lim et al. (2020)	Manufacturing sector/India

4. Results and findings

4.1. Phase 1: qualitative study: decarbonization framework for food supply chains

The framework adopted to analyse and suggest strategies for FSC stakeholders is an amalgamation of TOE with the sustainability pillars and personal dimensions. Table 1 gives the definition of each variable under the respective dimensions.

Under the technological dimension, DT and I4.0 are considered. Here, DT refers to technology that helps reduce carbon emissions in an SC, namely the use of clean technology, eco-friendly packaging for food, and green software and hardware systems that create carbon sinks and control the total carbon emissions throughout the FSC. I4.0 comprises technology driven by AI and ML that focuses more on automation and electrification and results in large-scale carbon emission reductions.

The second dimension pertains to organizational practices and consists of eleven variables. These variables relate to low-carbon practices and procedures in the FSC. The variables are optimized networks (ON), employee training (ET), top management support (TMS), reverse logistics (RL), lean practices (LP), low-carbon logistics (LCL), carbon efficiency capability (CEff), system integration (SysI), data sharing (DS), supply chain collaboration (SCC), and low-carbon sourcing and production (LCSP). LCSP means low energy-intensive production during farming activities, and includes cover cropping, reducing the tillage intensity, crop rotation, and organic farming, among other things. The use of wind turbines and solar-powered pumps is an example of options for irrigation that require lower energy consumption. Low-carbon operations during processing and distribution include reducing batch processing, proper heat recovery, optimizing the number of trips, and the use of biodegradable packaging, to mention a few. Similarly, in retail stores and warehouses, occupancy sensors, the use of daylight, and green buildings are a few energy-saving mechanisms. ET and TMS, along with SCC, are specific firm-level initiatives that also have implications for the SC. All these organizational activities are incomplete without data sharing and system integration for centralized decision-making. Under social dimension, CSR occupies a special place as it refers to creating a brand image for future collaboration and influences the adoption and non-adoption of specific technology during SC operations. Lean practices are organization-driven activities that reduce waste in the SC and enhance carbon efficiency in all operations. A key contributor towards carbon reduction within the organizational dimension is reverse logistics, which refers to the reuse, recycling and refurbishment of returned products; this creates a carbon sink in the FSC and ensures waste reduction.

After the organizational dimension the next important dimension of interest identified in the study is the personal dimension, which includes individual commitments and responsibilities that help operationalize the implementation of the strategy. The personal variables identified in the study are environmental consciousness (EC) and interdisciplinary team skills (ITS).

The key variables pertaining to the sustainability pillars, namely the social, economic and environmental dimensions, make up the 'SEE' of the 'TOPSEE' framework. Here, the social dimension covers five important variables: job creation (JC), health and safety (HSf), government support (GS), social integrity (SoI), and human centricity (HC). In the economic dimension, the variables are economic growth (EG) and reduced supply chain cost (RC). To achieve continued growth in the FSC through decarbonization, a cost reduction perspective is a sustainable plan. The environmental dimension of the TOE framework is one of the sustainability pillars and consists of external forces such as international community pressure (ICP), stakeholder pressure (SP) enforcing the use and promotion of energy-efficient operations throughout the FSC, and regulatory requirements (RR). These external forces help initiate the necessary rules and regulations for controlling carbon emissions in the SC using a carrot and a stick approach. The twenty-six variables identified under the TOPSEE framework are detailed in Table 1. These were further studied for their relative ranking using AHP and the hierarchy was then studied using an ISM approach. The results of the hybrid approach of AHP and ISM for the Indian FSC are presented in the following section.

4.2. Phase 2: quantitative study: the ranking and hierarchy of the identified components/constructs

This paper now presents the stepwise AHP results. First, the weighting among the dimensions of the TOPSEE framework is presented and then, in the second step, the rankings among the variables within each dimension are presented. Experts from ten firms helped to evaluate the criticality of the identified factors. Table 2 details the AHP results for all the variables belonging to the six dimensions. The AHP analysis reveals the highest priority, 0.39 out of 1, for the environmental dimension among the six dimensions being studied. The weights in decreasing order for the remaining five dimensions are 0.18 for technological, 0.12 for organizational, 0.10 for economic, 0.09 for personal, and 0.07 for social. Among the variables, the highest rank (1st rank) is given to ICP, belonging to the environmental dimension, which is the dimension that has the highest priority. The lowest ranking is obtained for LCSP. This variable belongs to the organizational dimension.

The ISM approach places all the variables of the TOPSEE framework into different hierarchical levels on the basis of the driver and dependence powers of each variable. The levels denote the propagation of relationships from the variables at the bottom, RR and ICP, to the topmost variables, DFSC and EG. Fig. 2 illustrates the path towards the DFSC and EG, and shows that tremendous and careful efforts are required to channel resources and follow specific practices to lower the carbon emissions from farm to fork. Fig. 3 presents the driver and dependence power of each variable in the structure, the y-axis being the driver power and the x-axis being the dependence power. The whole graph is divided into four quadrants, depicting four categories of variables that share similar characteristics. Fig. 2 portrays the driver variables, with the variables with the highest driving power in the group from level XIII up to level X. There are six variables in this group: ET, TMS, GS, RR, ICP and GS. In Fig. 3, these six variables fall into the driver cluster. The dependent variables, placed between level III and level I, number five: RL, CEff, RSCC, EG, and DFSC. These fall into the dependent cluster, hence their name. Among these, DFSC is the outcome variable in the study. The third group of variables, sandwiched between the dependent and the driver variables, are the linkage variables in the study. A total of sixteen variables are linkage variables: LCL, LSCP, LP, ON, DT, CSR, JC, SCC, DS, SysI, SoI, HSf, EC, I4.0, ITS, and HC. These can be observed in the linkage cluster in Fig. 3. Other details of the ISM results concerning the driver and dependence values of each variable are presented in the supplementary subsection S4.1.2.

Table 2
AHP results for variables and dimensions under the TOPSEE framework.

Dimension	Weighs	Variables	Weight	Final Rank
Technological	0.18	Decarbonization technologies (DT)	0.61	2
		Industry 4.0 technologies (I4.0)	0.39	4
Organizational	0.12	Optimized networks (ON)	0.07	21
		Employee training (ET)	0.12	15
		Top management support (TMS)	0.15	11
		Reverse logistics (RL)	0.06	26
		Lean practices (LP)	0.13	14
		Low-carbon logistics (LCL)	0.06	22
		Carbon efficiency capability (CEff)	0.06	25
		System integration (SysI)	0.09	18
		Data sharing (DS)	0.10	17
		Supply chain collaboration (SCC)	0.08	19
		Low-carbon sourcing and production (LCSP)	0.06	27
Personal	0.09	Environmental consciousness (EC)	0.60	7
		Interdisciplinary team skills (ITS)	0.40	10
Social	0.07	Job creation (JC)	10.24	23
		Health and safety (HSf)	24.15	12
		Governmental support (GS)	22.59	13
		Social integrity (SoI)	9.83	24
		Human centricity (HC)	19.52	16
		Corporate social responsibility (CSR)	11.75	20
Economic	0.10	Economic growth (EG)	0.61	6
		Reduced supply chain cost (RC)	0.38	9
Environmental	0.39	Decarbonized food supply chain (DFSC)	0.13	8
		International community pressure (ICP)	0.41	1
		Stakeholder pressure (SP)	0.17	5
		Regulatory requirements (RR)	0.25	3

5. Discussion

This section discusses the results of the ranking and hierarchy obtained from the hybrid AHP–ISM approach. The study compares different regional works and provides directions for the Indian FSC. Section 5.1 discusses the framework that answers the first research question, while Section 5.2 discusses the takeaways for Indian food supply chain players. Further, Section 5.3 discusses the variables contributing to the decarbonization of the Indian food supply chain, with an exhaustive discussion of the results from the AHP and ISM, and focuses on the second and third research questions.

5.1. Decarbonization framework in the food supply chain: a multi-stakeholder perspective

Designing a decarbonization strategy in the FSC requires a multi-stakeholder perspective, as there is a network of players who make up the whole SC. The players need to understand that a shift to a low-carbon economy has to be accomplished properly. The players that will benefit from such a transition are green producers and aligned industries. However, to achieve sustained economic growth for such players, there is a need for a strategic plan. The adoption of alternative fuels is essential for the transition to a low-carbon economy. Hence, it is equally important that reliable data on emissions is shared between SC players in order

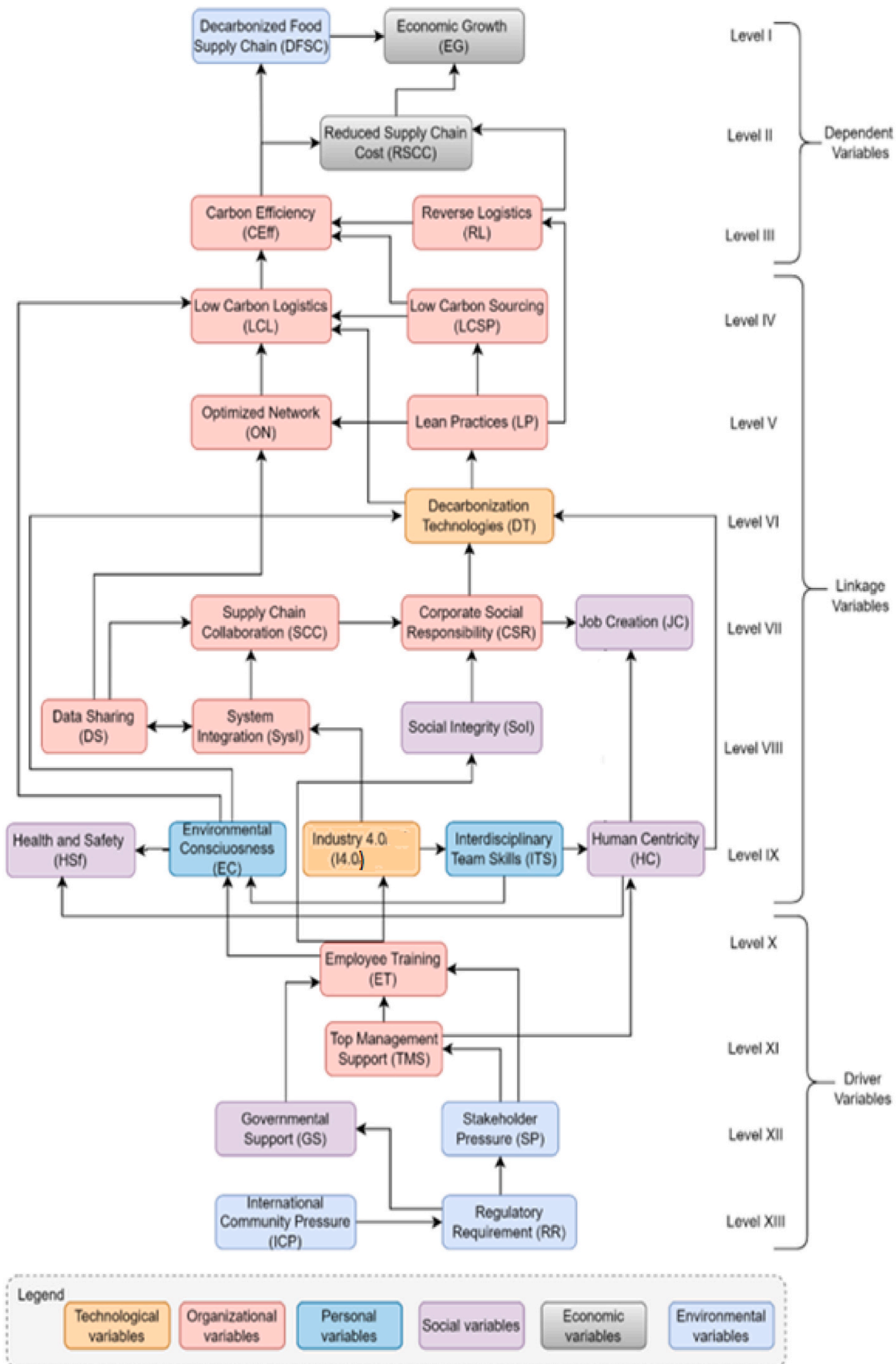

Fig. 2. ISM digraph for decarbonization practices in the Indian food supply chain.

to enhance decarbonization in the food ecosystem. Low-carbon innovative solutions are also costly and therefore face funding and technical challenges that need to be addressed. With the right technical and financial support, these obstacles could be overcome to attain a sustainable future in India (Kumar et al., 2023; Sharma et al., 2021).

The TOPSEE framework of the present study opens up a pandora of opportunities and challenges for achieving a low carbon footprint for the Indian FSC. The decision framework presented in the study will help the FSC players to understand the role of each decision variable and its impact on their current scope of business. The decarbonization approach will bring opportunities and challenges to the FSC players. The TOPSEE framework will enhance the understanding of the need for the design of carbon-efficient processes and practices, and of the requirements in India.

5.2. Takeaways for Indian food supply chain players

1. ***Producers/Farmers:*** The framework considers the practices of low-carbon sourcing and production for achieving decarbonization. For producers, traditional farm practices could be replaced with organic farming, which has the potential to reduce carbon emissions by carbon sequestration through low tillage, crop rotation, the use of organic fertilizers, and proper livestock management. Likewise, traditional producers can leverage and transition to become green producers and explore energy-efficient and cost-effective innovations in farm practices. However, this transition could be a

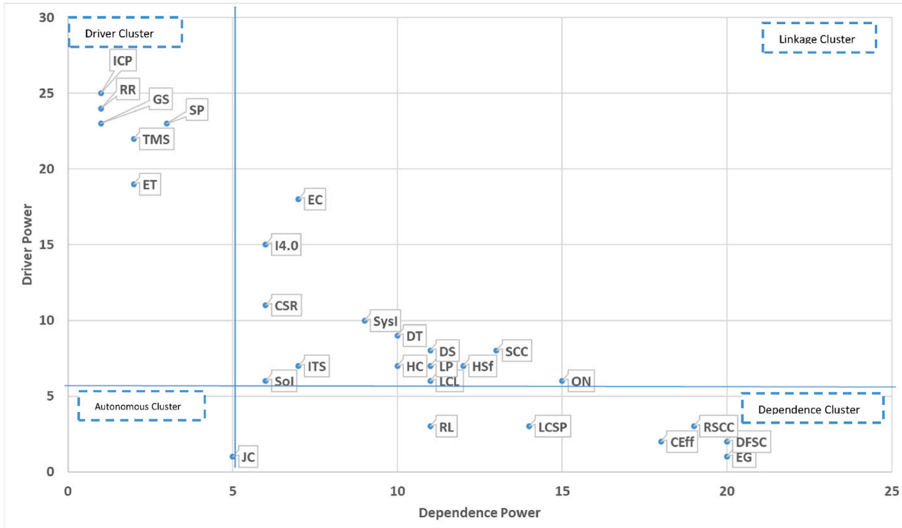

Fig. 3. MICMAC analysis for decarbonization variables in the Indian food supply chain (Note: Decarbonization technologies (DT), Industry 4.0 technologies (I4.0), Optimized networks (ON), Employee training (ET), Top management support (TMS), Reverse logistics (RL), Lean practices (LP), Low-carbon logistics (LCL), Carbon efficiency capability (CEff), System integration (SysI), Data sharing (DS), Supply chain collaboration (SCC), Low-carbon sourcing and production (LCSP), Environmental consciousness (EC), Interdisciplinary team skills (ITS), Job creation (JC), Health and safety (HSf), Governmental support (GS), Social integrity (SoI), Human centricity (HC), Corporate social responsibility (CSR), Economic growth (EG), Reduced supply chain cost (RC), International community pressure (IC), Stakeholder pressure (SP), Regulatory requirements (RR), Decarbonized food supply chains (DFSC).).

costly affair for producers. For this reason, government support is essential for incentivizing the mass adoption of these practices. Foreseeing the future in green energy, and investment in this, could be a strategic move for the producers. Growth in this sector is immense and will require state and central government intervention. Investment in green practices by angel investors and the provision of technical know-how through Krishi Vigyan Kendras is the future for sustainable adoption.

2. Processors: It is argued that preservation and processing activities make a great contribution to carbon emissions. Hence, it is essential that businesses carrying out processing activities find cost-effective and carbon-efficient preservation practices to follow during food processing. Much could be done by using biofuels and clean energy for packaging and labelling purposes. Cost-effective preservation and processing activities include drying techniques such as sun drying, vacuum drying, and freeze drying. To motivate processors to adopt green practices, timely incentives for infrastructure development and training could be game changers. Also, emissions during processing activities could be controlled by digitalizing processes, which would help with the accurate measurement of carbon emissions.

3. Aggregators/Distributors: The TOPSEE dimensions could help these players in formulating strategies to achieve low-carbon practices during their distribution and warehousing activities. Distributors would need to move towards clean energy practices and to partner with green producers/players specializing in green vehicle technologies. To reduce carbon emissions, distributors will also need to plan optimized routes, which could be very cost-effective. Second, they could invest in electric vehicles for transportation purposes, and battery-driven/automated forklifts for warehouse operations. Warehouses can also ensure optimal energy usage through occupancy sensors.

4. Customers/Consumers: The dietary patterns of consumers have an immense influence on the demand for food products (Grosso et al., 2020). When this food requires higher energy for production or processing, carbon emissions also rise. Consumers can proactively make conscious choices among the large varieties of food available in retail stores. Similarly, retailers, along with processors and producers, need to collaborate and launch low-carbon diets for consumers. Creating an awareness programme for this type of products is essential for boosting intelligent and smart choices by customers.

5.3. Variables contributing to the decarbonization of the Indian food supply chain

5.3.1. The drivers of decarbonization

The present study attempts to create a holistic picture of the role of twenty-six variables in decarbonizing the FSC through digitalization. The essential actuators in the system lie at the bottom level of the hierarchical structure of the ISM in Fig. 2. These belong to the environmental dimension, and include international community pressure, regulatory requirements, and stakeholder pressure. Lim et al. (2020) and Khan et al. (2021) explained that external forces help in the formulation of business strategies. These external forces act as enforcement agencies in the design of industry-specific market strategies such as policies on carbon tax, and the enforcement of eco-labelling and green SC practices. Also, there are climate policy advisors that assist SC partners in understanding the impact of these opportunities and risks on their operations (Singh et al., 2021). Emission-based taxes are a perfect market tool for indirectly reducing carbon footprints through trade. If such policies or regulations are not in place, it is impossible to formalize and enforce the control of emissions. It is also essential to imbue SC members with a mutual understanding about controlling emissions, otherwise each player will attempt to make individual gains.

Diniz et al. (2021) and Annosi et al. (2021) remarked that the re-conceptualization of SC operations through digitalization could be fostered through institutional forces along with stakeholder pressure. Nouni et al. (2021) also concluded that the usage of biofuels and compressed natural gas, although it provides opportunities for decarbonizing the supply chain, requires policies for enforcement. The role of external regulations has been discussed in the Indian transport sector. In the food sector, the regulations for ensuring safe and healthy food have been expounded by Khan et al. (2021). It is noteworthy that India lacks an explicit carbon tax. Most of its carbon taxes are implicit (the coal cess and renewable energy certificates). Ojha et al. (2020) stated that an explicit carbon tax has yet to be formulated for controlling carbon emissions in Indian SCs. India, along with several other countries, has committed to reducing carbon emissions, but this may become difficult to achieve if the carbon tax is not formalized soon. To fulfil consumers' requirements for green products, producers and distributors must align their products and services accordingly. There has been a surge in the usage of recyclable packaging material; for example, biodegradable packaging is expected to grow at a compound annual growth rate of 6.10% according to the global green packaging market overview.

The variables in the social dimension, such as governmental support, belong to the driver cluster. This implies that, in order for firm-level decisions to be formulated and implemented, support from the government is indispensable. The subsidies and incentives for industries announced by the government are stimuli for the top management to design strategies for decarbonization. Talbot et al. (2021), Annosi et al. (2021), and Adams et al. (2023) have argued that a lack of government support and stakeholder pressure may turn out to be a disaster, as it will act as a barrier to the very purpose of promoting green practices. External climate change forces act as advisers for how to control the amount of carbon in SC processes. The existing schemes for farmers and FSC players for reducing carbon emissions include Paramparagat Krishi Vikas Yojana (PKVY), which encourages farmers to adopt organic farming, which also indirectly improves soil health, reduces the use of synthetic fertilizers, and offers farmers improved market opportunities for their organic produce. As part of the sustainability bandwagon, multinational corporations have linked up directly with producers for green products and services. To fulfil the mission of becoming carbon neutral by 2070, as emphasized in the COP26 summit, action-driven coalitions and co-investment in sustainable production are the ultimate key. Luthra and Mangla (2018) stated that governmental schemes and stakeholders' awareness play an important role in pushing industries to adopt decarbonization practices. Government plans can also encourage private investors in green initiatives in order to transition towards a net zero future.

Top management support and employee training are the next highest priority variables, and are ranked among the top 15 in the AHP analysis. In the majority of studies, these variables have been claimed as major driver variables for any change management. Among these studies are those of Yadav et al. (2022) and Emamisaleh and Rahmani (2017), who claimed that top management support was an internal driver for achieving sustainability. Alongside this, awareness among employees regarding carbon-intensive processes and the accurate measurement of emissions could be enhanced through providing timely training to employees. Xu et al. (2023b) and Lin et al. (2023) have claimed that training is an essential part of any organizational practice so that employees become comfortable with technological innovations. These authors highlighted energy-efficient practices in food, such as the adoption of low power factor equipment (microbial fuel cell technologies (MFCT)) for harvesting, processing, and warehouse operations. Oh and Logan (2005) and Khan et al. (2017) found that MCFT has tremendous cost savings in the long run. Indian FSC needs to give immediate attention to such technologies as they produce electricity from food waste, which is a great opportunity considering the amount of food waste generated every day. Sovacool et al. (2021) highlighted a very important fact: from the initial stages of production of food until its final utilization, the influence of food consumption on energy, water, climate change, and other ecological factors is consequential. Therefore, to make energy savings and lower the overall cost of the SC, the top management needs to initiate and support training programmes promptly as technologies also become obsolete over time.

5.3.2. Linkage variables boosting decarbonization

In the MICMAC analysis, the highest number of variables is found in the linkage cluster, which consists of fourteen variables. In the ISM structure, these are observed to lie from level IV to level IX. These variables include those in the technological dimension (decarbonization and I4.0 technologies), seven variables in the organizational dimension (low carbon sourcing and production, low carbon logistics, lean practices, optimized networks, supply chain collaboration, data sharing, and system integration), variables from the personal dimensions (environmental consciousness and interdisciplinary team skills) and the five variables under the social dimension (health and safety, job creation, corporate social responsibility, human centricity, and social integrity). The position of the variables in the hierarchical structure implies that the very existence of driver variables (institutional pressures such as international community pressure and stakeholder pressure) is a prerequisite to operationalizing the variables in the linkage cluster. For any interventions to be formalized and enforced, drivers enable the linkage variables to achieve the outcome variable. As the major role of the linkage cluster is to accelerate the decarbonization process, this could be achieved through I4.0 technologies customized for the FSC. The present study found that employee training, an important driver variable, connects with the I4.0, which belongs to the linkage cluster. In India, the concept of smart agriculture is spreading as players have started realizing its positive impact. Smart agriculture practice includes the use of IoT-based tools for studying soil moisture, crop health, and carbon emission measurement during processes, which is found to reduce food waste and control emissions. Nagarajan et al. (2022) proposed an IoT-based dynamic food supply chain for smart cities, to monitor and manage the food industry and ensure food quality. The system, in addition, would provide intelligent vehicle routing and allow sources of contamination in FCM to be traced. A smart sensor data collection strategy based on the IoT would be implemented to enhance the efficiency and accuracy of the supply chain network. The proposed system is far superior to the existing methods. A few studies that have highlighted food waste reduction through digitalization in developed economies are those of Annosi et al. (2021), Xu et al. (2023a), and Oltra-Mestre et al. (2021). A very recent study by Rizan et al. (2023) presented an IT tool for systematizing the process of identification, the definition, the rationale, and the impacts of carbon-intensive activities in the automobile industry. A similar tool could be developed and a feasibility analysis could be carried out for the Indian FSC. There are a few Indian studies – those of Khan et al. (2017) and Ajwani-Ramchandani and Bhattacharya (2022) – that have discovered barriers to the implementation of I4.0 practices in the Indian FSC. Yadav et al. (2022) explored the role of technology in making a FSC smarter, but this study lacks empirical evidence in the Indian context. Studies are mostly concentrated in economies such as Spain (Oltra-Mestre et al., 2021), the UK (Cricelli et al., 2022), Europe (Román-Collado et al., 2023), and Latin America (Peréz-Morón and Cantillo-Orozco, 2022). In developing economies such as Vietnam (Akbari and Hopkins, 2022; Bui et al., 2023) and Brazil (Peréz-Morón and Cantillo-Orozco, 2022), studies are still evolving but lack empirical evidence.

Environmental consciousness is an outright solution for initiating practices for decarbonizing SCs, as explained by Wang et al. (2022). This variable ranks among the top ten variables in the study. This implies that customers and employees influence firms' adoption of resources. Their behaviour towards the environment and willingness to make low-carbon purchases influence firms to promote low-carbon products and services. Kautish et al. (2019) established empirical evidence for the role of environmental consciousness in enhancing green practices in Indian SCs. Environmental consciousness in India is often discussed in the context of consumer behaviour and the choices made by consumers in favour of environmentally friendly food packaging (Popovic et al., 2019). Although not much work has been done on environmental consciousness in the FSC, one study by Hakkim et al. (2016) has discussed it in precision farming. In a global scenario, the variable has been shown to have top priority in adopting organic food and related practices (Krejci and Beamon, 2014). As customers become more environmentally conscious, sustainable behaviour is also expected from producers. An employee awareness programme in the industry and continuous motivation can boost a firm to align its processes to the customer's requirements. This consciousness has also encouraged businesses to automate processes and, thus, reduce waste and energy costs. The green packaging market has immense potential as it is expected to grow at a compound annual growth rate (CAGR) of 6.1% in 2027.

Human centricity has an important role as a catalyst in creating a safe and healthy environment in SCs, as set out by Sharma et al. (2022e). The variable ranks among the top 20 in this study. A human-centric approach is an emerging area of research that is discussed by Ivanov (2022). This variable is also an important dimension that was highlighted by the Japanese government in 2016 as being crucial for Society 5.0, as asserted by Huang (2022). The current study claims that the variable is highly relevant in the context of SCs as it covers intertwined SCs involving several human interactions. As part of human centricity, organizations adopt flexible and adaptable practices for promoting system agility and ensuring SC resiliency (Wang et al., 2022). The concept has currently been adopted in developed nations, as explained by Henriksen et al. (2022) and Ivanov (2022). A handful of studies have also observed this in India: the study by Khan et al. (2023) discusses its advantages over I4.0. The majority of studies are focused on SCs other than the FSC, and on developed nations. The Indian FSC, which faces its own challenges, would benefit from such customized practices. However, employees need to be trained to use customized tools and equipment, and this requires the building of interdisciplinary team skills. These skills are essential for understanding and implementing predictive maintenance by employees and adopting collaborative robots to enhance process efficiencies. Although customization comes with an intensive cost structure, it will guarantee a long-term profit, as claimed by Javaid and Haleem (2019).

The next agglomeration of variables falling within the linkage cluster belong to the organizational and social dimensions. These play an important role and include variables such as system integration, data sharing, supply chain collaboration, corporate social responsibility, and social dimensions such as social integrity and job creation. One great object of admiration is the job opportunities resulting from customization and personalization through the introduction of human centricity and green products in SCs. A human-centric approach is believed to lead to human-centred designs that will require research and foster collaborations among countries as well as within countries for acquiring talent (Ivanov, 2022). The fact that job creation emerges as an autonomous variable in the study emphasizes that, when considering decarbonizing the Indian FSC, creating job opportunities is not the ultimate focus; instead, the existing resources must be trained to decarbonize the SC through technological innovations. In the literature, job creation has also taken a back seat in Indian SCs although it is considered an important variable in the context of developed nations in the studies of Barney et al. (2022) and Abram et al. (2022).

Data sharing and system integration, at level VIII with social integrity, refer to disclosing the sources of carbon emissions. Nayeri et al. (2023b) emphasized that data sharing and collaboration are essential elements for carrying out customization in healthcare systems. The accurate measurement of carbon sources and their control through a joint effort should be the strategy of every player in the SC. Logistics and warehousing operations cannot always be blamed for carbon-intensive operations: operations related to preservation and processing are also culprits in emitting carbon. One estimate indicates that the total emissions from food industries are between 1.9 and 3.8 Gt CO_2-eq. annually, with between 53% and 77% of this being unreported (Sovacool et al., 2023). Given this lack of reporting of value chain emissions, the food sector must immediately increase the reporting and management of greenhouse gas emissions if it is seriously concerned with reducing the climate impact. Also, industries need sector-specific frameworks to address this concern. Hence, ways for measuring emissions from these industries that are effortless and relevant should be ensured when making strategic plans.

Any transformation journey requires trustworthy data for a successful strategic move. Dixit et al. (2021) stated that to ensure integrity in a multi-channel network, proper data exchange through communication channels requires the design and adoption of digital platforms. On this journey, negligence in social integrity will make all efforts vain, as demonstrated by Johns et al. (2013). Food faces challenges concerning the bullwhip effect in SCs, which results in lost sales and low profit margins. However, such a scenario makes it unattractive to embark on any paradigm shift in SCs. Hence, to reduce carbon emissions in the food supply chain with a multi-player scenario, data integrity is a prerequisite. Data integrity is also crucial for ensuring the transparency of data and the effective tracing of food during any food recall. Organizations are now being scrutinized and required to reveal their activities under the broad environmental, social, and governance (ESG) umbrella. ESG is a set of criteria for the assessment by stakeholders and investors of a company's ethical impact and sustainability. However, if data are not available then there will be a failure to create a measurement system, whether it be for identifying and measuring the extent of carbon emissions or for ESG reporting.

Progress along the roadmap for achieving decarbonization in the Indian FSC could be accelerated by designing the right corporate social responsibility strategies for businesses. Corporate social responsibility is the ninth important linkage variable and is considered a powerful industrial tool for carbon reduction. It is ranked twentieth among all the variables studied. The strategies of corporate social responsibility include setting carbon emission targets internally, and collaboration through partnerships for co-designing best practices for decarbonization. Kumar et al. (2023b) in the Indian economy and Zhou et al. (2024) in the Chinese economy emphasized the role of corporate social responsibility in the adoption of decarbonization technologies, corroborating the results of the present study. In our study, the power of a linkage variable to make changes to the variables that it influences is similar to the power of the variables that influence it (which in this case is social integrity, lying below CSR at level VIII). This leads to the important conclusion that driver variables such as environmental pressures have to outperform so that the linkage variables can successfully help to achieve the outcome variables in the study (a decarbonized FSC and economic growth). Indian corporates have taken various initiatives to create brand images for future collaborations with green producers. These collaborations, through green projects like renewable energy, help to offset their carbon emissions.

Lean practices and optimized networks are important variables in the organizational dimension that were shown to fall within the linkage cluster during the MICMAC analysis, with the former attaining a lower rank in the AHP analysis than the latter. These two variables have been identified as driver variables in the majority of studies in the manufacturing (Al-Refaie et al., 2020; Farrukh et al., 2022; Yadav et al., 2022), fresh food (Sharma et al., 2023a), and construction (Challa and Rao, 2022; Hong et al., 2022) industries. The reason for this difference is that the present study also considers desirable variables for creating an environment for lean practices in the FSC ecosystem. Decarbonization technologies are also effective in achieving lean practices by reducing waste and ensuring low carbon emissions through automation. Encouragement and support from top management in creating awareness through proper training during the conception of lean practices is necessary to avoid individual gains. Solutions like least-cost methods that involve planning optimized networks in logistics operations also lower emissions and waste. Businesses following lean practices are also careful to embed environmental requirements into their procurement contracts, ensuring low-carbon sourcing and production. This is in line with the studies of Alghababsheh et al. (2022) and Sharma et al. (2023d), which were conducted in a manufacturing context. Smart solutions such as the use of fuel-efficient systems in logistics and warehousing operations reduce fuel consumption and hence emissions, corroborating the studies of Rao and Li (2022) and Das and Jharkharia (2019). These studies emphasize that low-carbon procurement and product design are crucial in achieving SC sustainability in the manufacturing sector. India has been able to bring in innovations such as smart grids, AI-based precision farming for optimizing fertilizer usage, drip irrigation designs, the identification of low-carbon sources, and efficient logistics systems (Anitha Mary et al., 2022). Among the handful of studies in food, Singh and Shabani (2016) investigated how low energy-intensive operations in logistics can reduce the carbon footprint in SCs.

5.3.3. The dependent variables

Increased awareness of climate change has fuelled the opportunities for reverse logistics. This is another crucial variable in the organizational dimension, and is ranked twenty-sixth in the AHP analysis. Jabbour et al. (2020) emphasized the commendable role of I4.0 in the effective planning and implementation of reverse logistics activities in SCs. Liao et al. (2017) proposed that economic growth could occur through the proper disposal of products and the realization of value from returned products to reduce cost. Moreover, the reuse and recycling of the products at the end of their useful life requires partnering with refurbishing companies and technology providers. These practices aid in achieving the objectives of the circular economy, which focuses on regenerative processes and reusable products. Product returns are much more challenging for perishable food than they are for non-perishable food items. Food products may be returned because of poor quality, allergy issues, or food safety, among other reasons. The proper training of employees for managing returns is essential for effective returns management. As agricultural land acts as a carbon sink, the management of returns offsets the carbon emissions.

Undertaking production and distribution activities with a minimized carbon footprint is carbon efficient, and several economic studies have expounded on this in different sectors: manufacturing (Luo et al., 2022; Jiang et al., 2022) food (Gu et al., 2023; Ren et al., 2023) and construction (Jiang et al., 2022; Wang et al., 2022). Optimal energy consumption significantly reduces carbon emissions. Our study claims that reverse logistics has an impact on achieving carbon efficiency. Similar results are observed in the studies of Sun (2017), Choudhary et al. (2015), and Guo et al. (2017) in a non-FSC context. Reddy et al. (2019) along with Kazancoglu et al. (2021) conducted similar studies on food, but in developed economies. Studies specific to the Indian FSC context are still evolving. Optimal energy usage could be achieved in all the activities from farm to fork through the digitalization of processes and through cost-effective practices such as optimized networks (ON) for distribution purposes during logistics operations. Practices such as low-carbon sourcing and production (LCSP), the design of optimized and smart lighting in retail stores, and intelligent consumer purchases of low-carbon products are a few of the activities that have been identified as having an amplifying impact on controlling carbon emissions along the chain.

The digitalization of the FSC requires the identification and design of cost-effective practices and processes to shrink the carbon footprint. The present study identifies the top-level variables as decarbonized FSC and economic growth, which are found at level I of the ISM analysis. However, a reduced supply chain cost lies at the level below these two. The reduced cost and economic growth variables belong to the economic dimension, and decarbonized FSC belongs to the environmental dimension. If the variables are arranged in decreasing order of rank from the AHP analysis, the order is economic growth, decarbonized FSC, and reduced cost. The current study finds that carbon efficiency reduces the supply chain cost and ultimately achieves a decarbonized FSC. It also finds that decarbonization through low-cost technological interventions will lead to economic growth in the FSC. This finding is in line with the study by Hildingsson et al. (2018), which was carried out in the context of developed nations. Some other authors who have highlighted these relationships are Wójcik-Jurkiewicz et al. (2021), Fouquet and Hippe (2022) and Bataille et al. (2016). These studies conclude that long-term economic growth will be ensured in the context of food only if low-carbon technologies are designed and operationalized. This will require carbon-efficient systems to be identified, which needs heavy investment by Indian firms. As the FSC encompasses small-scale players who are the backbone of the economy, these players need to be nurtured and groomed through proper financial and infrastructural support to make their businesses profitable. Also, automation could be a good option for these players to make the transition cost-effective. In this regard, the careful design and implementation of practices involving multiple stakeholders will reduce carbon at the lowest cost.

This paper describes a journey from external forces to the necessary and supporting processes and practices for achieving decarbonization in the FSC. Such an exhaustive framework requires a multi-stakeholder contribution and a perspective that can help disseminate data, equipping the FSC for a paradigm shift.

6. Implications

This study has various implications for managers, practitioners, and researchers.

6.1. Theoretical implications

This research covers various critical constructs, including different significant domains such as technological, environmental, organizational, economic, and personal characteristics. The study bridges TOE, the triple bottom line, and personal characteristics to provide a comprehensive list for future researchers and practitioners. Implementing these practices can lead to an efficient carbon-neutral supply chain, creating a cleaner, healthier, and more sustainable environment for future generations. The foremost technological aspect emphasizes the need for Industry 4.0 and automation processes for decarbonization and reiterates the conclusions of Brinken et al. (2022a) and Mishra et al. (2023). Smart technologies can seamlessly and efficiently facilitate and accelerate manufacturing, leading to more sustainable operations by reducing carbon emissions. Varavallo et al. (2022) and Sheng et al. (2023) posited that greater emphasis on green products is only possible with Industry 4.0 (Ali et al., 2021; Kayikci et al., 2022) and smart automation, which provide solutions for the redesign of conventional processes and ensure transparency and better public health. The economic advantages of Industry 4.0 comprise reduced costs and profitability in the long run, as there is a first-mover advantage for industries integrating eco-friendly steps. Selecting suppliers in the close vicinity can also reduce travel time and fuel consumption, thereby cutting carbon footprints. Collaboration with agents and suppliers can lead to greater economies of scale. Industry 4.0 mechanisms also help in managing inventories and stock effectively, reducing wastage. The optimization of energy usage in the food supply chain can reduce the emissions of pollutants. This study ranks the twenty-seven constructs through AHP, providing managers with a roadmap for sustainable supply chain initiatives. The implementation of these major changes can improve people's quality of life by promoting healthy and nutritious food consumption and an understanding of the importance of a cleaner environment, and contributing to a healthy future. This interplay of the relevant drivers could stimulate the implementation of sustainable processes in industry and help managers propose better strategies to design efficient, carbon-free food supply chains.

6.2. Practical and policy implications

There is an increasing trend towards decarbonization and carbon neutrality, with entire economies, cities, and multinational organizations pledging to achieve these goals. These endeavours indicate a positive shift along the road. The rationale for this transition is twofold: first, it enables industries and nations to narrate a different story about their ecological impact, and secondly, it helps to shape future frameworks and consequences. When we deliberate about climate change or carbon footprints, we rarely consider agriculture as a priority industry. However, the sectors that comprise this industry are critical links in the attempts to regenerate our planet. As in any industry, there are entrepreneurs on this path who are aspiring towards carbon neutrality. Some large companies, such as Danone, Nestlé, Olam International (a major global supplier of food ingredients and commodities), the food service giant Sodexo, and PepsiCo Inc., have agreed to a UN-promoted undertaking to regulate their emissions to enable global warming to be restricted to 1.5 °C (Brasher and Pagel, 2020).

In line with this thought, this study has six practical implications. First, integrating efficient technology to minimize carbon emissions requires significant investment, which often leads to initial losses and no trace of profits. This cash deficit deters industries in the food supply chain from adopting sustainable measures, and forces them to continue with conventional, cheaper, and inefficient processes. Therefore, innovation and the implementation of sustainable practices for food supply chain industries is imperative. Second, the limitations encountered by managers are usually linked to the systems and processes in the food supply chain. Designing efficient systems requires rethinking and reworking processes, which necessitates greater investment and effort. The gradual scaling up of processes before demand arises can be an effective strategy to avoid sudden disruptions. Third, the food supply chains for fresh, perishable, and non-perishable foods require different systems. The problem of food wastage is critical because it reduces food availability and uses up the resources required to acquire food for future generations (Pandey, 2021). Dora et al. (2022) posited that adopting AI as a solution to minimize food wastage through better processes can be beneficial. Fourth, it is imperative to manage the refilling or renewal of inventories to ensure the freshness of food products. Sustainable food supply chain systems should focus on reducing the carbon emissions that occur through the handling of material, transportation, and because of the particular characteristics of food products, by creating energy-efficient automation in transport and food preservation. Fifth, sustainable food supply chains are created by the joint efforts of government policies that encourage food supply chain members to commit to green technology and green initiatives by their customers. Leveraging economic incentives, introducing carbon pricing methods, or having subsidized rates for low-carbon technologies can assist with the economic indications. Governments can consider implementing an extended producer responsibility (EPR) on the manufacturer to persuade manufacturing industries to issue maximum pollutant information declarations (Choi and Siqin, 2022). Sixth, a well-informed, aware, and skilled workforce is capable of driving environmentally friendly practices to ensure a better and healthier environment. Governments and industries can reach out to communities and NGOs in their locality to work on productive measures for the larger society, thereby initiating symbiotic practices.

6.3. Societal implications

The inability of industries and individuals to amalgamate different frameworks to minimize decarbonization and global warming can result in ecological degradation, leading to greater climate change and a global catastrophe. Decarbonization is not merely a theoretical concern, but a real-world problem for the global ecosystem. This study has multiple implications for society, including the need for industries to increase their transparency and accountability by integrating automated systems to trace and share data about the carbon footprints in their supply chains. This can facilitate the building of trust with consumers, leading to greater sales and profits. By prioritizing decarbonization, industries and firms can sign up to a sustainable society with reduced carbon emissions, which can influence other industries to follow suit and create a cleaner, greener, and healthier environment. To encourage sustainability across sectors, industries can educate their employees about the merits of a green and sustainable supply chain, which can foster an ecosystem that prioritizes environmental concerns and expands beyond the organization. This study also underscores the significance of health and safety, job creation, and corporate social responsibility, which are always critical. Supply chains that prioritize social responsibility and address social problems contribute to a stronger society by establishing trust and strengthening the industry–consumer relationship, leading to economic profits. Finally, industries can contribute to preserving biodiversity, natural resources, and the overall health of the planet by proactively mitigating their environmental influence, creating a healthier, pollution-free planet for generations to come.

7. Conclusion, limitations, and future directions

The study is based on three research objectives. First, the TOPSEE framework was systematically identified and finalized with many deliberations from experts and a thorough literature review that was appropriate for understanding FSCs in India. The framework integrates the TOE, sustainability, and personal dimensions with a specific focus on decarbonization. The second research objective was to determine the priority among the various dimensions and variables within the dimensions motivating decarbonization. The results indicated the importance of the environmental dimension, followed by the technological, organizational, economic, personal, and social dimensions, as crucial for decarbonization in FSCs. The third research objective was to detail the relationship among all the variables to simplify decision-making in the close-knit supply chain. In a nutshell, there are many takeaways from the study. The **first** mandate applies across all FSCs because the vast population of India relies on the competency of FSCs to provide good, nutritional food to cater to the needs of nutrition and survival. Good food consumption is fundamental to the sustenance of good health and life itself, and can be facilitated with efficient FSCs. If immediate attention is not paid to maximizing the efficiency of FSCs, people's health will deteriorate through malnutrition, which will translate into many more health concerns. **Secondly**, industries in India can only achieve this goal by upgrading their machinery and supply chain processes with advanced Industry 4.0 automation, by monitoring the regulatory requirements, through international community pressure and stakeholder pressure, and by receiving support from the government. **Thirdly**, industries implementing low carbon emission supply chain processes gain a competitive advantage because consumers are becoming more conscious of environmental concerns and are drawn towards green and clean products, services, and the environment at large. The **fourth** concluding aspect is that industries can build people's trust by sharing their practices, which will multiply their sales and lead to greater economic benefits.

The limitation of this investigation is the mere focus on the FSC. The framework should be tested in multiple sectors to check its generalizability. Longitudinal studies will help to understand the real-time impact of all the variables, as they can focus on pre- and post-measures. These real-time values will help to modify the current relationships that have been identified. This study was carried out in a developing nation, India, and exploring the constructs in other developing economies as well as developed economies will give greater clarity to the measures to be implemented. As this investigation focuses on FSCs, scholars can explore constructs that are not associated with food, and assess their pertinence in diverse sectors. The Rotation Forest algorithm and the Logit Boosting algorithm could be investigated in the FSC in Indian Agriculture 4.0 to enable the government authorities to reduce credit risk, which is a significant hurdle in Agriculture 4.0 investments. Considering the systematic propositions of this study, a similar amalgamation of frameworks can also be considered in other industries.

CRediT authorship contribution statement

Mahak Sharma: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Conceptualization. **Rose Antony:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation. **Suniti Vadalkar:** Writing – review & editing, Writing – original draft. **Alessio Ishizaka:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142922.

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