

Critical Factors to Sustaileanant Innovations for Net-Zero Achievement in the Manufacturing Supply Chains

Vishwas Dohale^a, Priya Ambilkar^a, Sachin Kumar Mangla^{c,d,*}, Balkrishna Eknath Narkhede^b

^aBusiness School, Dublin City University, Dublin 9, Ireland; ^bOperations and Supply Chain Management (O&SCM), Indian Institute of Management, Mumbai, India ^cOperations Management, Jindal Global Business School, O. P. Jindal Global University, Haryana, India; ^d Knowledge Management & Business Decision Making, University of Plymouth, UK
(*Corresponding Author)

Abstract

The importance of reducing carbon emissions to safeguard the environment for generations is widely recognized worldwide. Countries are putting in efforts to lower their carbon footprint, aiming towards achieving carbon neutrality also termed as net zero emissions. This research seeks insights from manufacturing experts on how sustaileanant (sustainable + lean) innovations can support the journey towards net zero in manufacturing supply chains, making them more environmentally friendly. We initially determined the critical success factors (CSFs) of sustaileanant innovations that can help achieve net-zero emissions in manufacturing supply chains and validated through manufacturing experts using a validity survey. Further, employing a robust two-step approach involving strong ordering data envelopment analysis (SODEA) and machine learning (ML) based Bayesian network (BN), we aimed to understand the significant CSFs driving this transition from traditional carbon-heavy manufacturing practices to a net zero objective. Our study involved gathering input from 125 professionals in the manufacturing sector for employing SODEA-BN methodologies. The findings highlight that incentive schemes for organizations, availability of professional expertise, and availability of funds for implementing sustaileanant practices are crucial for organizations to transform and achieve carbon neutrality. In this study, the recommendations provided in line with sustainable development goals (SDGs) will guide practitioners and academicians in understanding the critical sustaileanant factors for a successful net-zero achievement.

Keywords – Sustaileanant Innovations, Net-Zero, Manufacturing Supply Chains, Strong Ordering Data Envelopment Analysis, Machine Learning, Bayesian Network

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1 Introduction

In the face of escalating environmental challenges and the urgent need to combat climate change, the concept of achieving net-zero emissions (NZE) has gained substantial traction. The global industrial sector struggles to transform its carbon-oriented business processes into carbon neutral to reduce its carbon footprints. The industrial supply chain and logistic network contribute significantly to carbon emissions (Mishra et al., 2022). The complexity of global supply chains involving multiple entities across different countries and continents, amplifies their carbon footprint (COP26, 2021). Long-distance transportation, reliance on fossil fuels, energy-intensive production processes, and waste generation contribute to supply chain emissions. It was estimated that global emissions driven by international trade through the worldwide logistics network would grow from 25% (Dellink et al., 2017; Janssens et al., 2020) to 30% and will further increase with a factor of 3.9 by 2050 (ITF, 2016; WTO, 2021).

The carbon footprint of supply chains can vary across industries and regions. Sectors such as manufacturing, transportation, and agriculture are known to have significant carbon emissions due to their extensive pollution levels and supply chain networks (Dohale et al., 2023c; Muthu, 2019). It has been observed that organizations globally are self-motivated to roll out different innovative solutions to manage their supply chains to make them carbon neutral. Utilizing the resources efficiently, adopting green technologies, and data-driven innovations trigger net zero emissions (Dohale et al., 2024; Mishra et al., 2022; Nyangchak, 2022).

One component of achieving NZE is the integration of sustainable and circular practices within global supply chains (Dohale et al., 2023c). On the other front, avoiding non-value-added activities for energy savings through lean practices can potentially contribute to ecological sustainability. For instance, using a lean approach, General Electric saved 35 million KWH of energy, equivalent to US\$ 3 million in energy costs saved per year and reduced 25,000 metric tons of CO₂ emission (General Electric, 2021). Similarly, Toyota Motors recycled, reused or used approximately 86% of an end-of-life vehicle's material content for energy recovery. This helped them to reduce GHG emissions at their nine plants by 50% by 2030 (TOYOTA, 2022). These examples illustrate the essence of lean and sustainable practices in the quest to combat climate change and achieve net-zero emissions (Cherrafi et al., 2018; Mathiyazhagan et al.,

2022). The body of knowledge, however, is still limited with the research on developing interpretable net-zero supply chains (Mishra et al., 2022). Thus, organizations face difficulties utilizing and executing lean and sustainable innovations to transform their supply chains to carbon neutral. Against this backdrop, this study aims to explore – 1) the concept of lean and sustainable innovations and its potential application in the context of attaining net-zero emissions; and 2) factors driving the smooth execution of lean and sustainable innovations to deploy carbon-neutral practices in their supply chains. The motivation of this research lays a foundation for the following research questions:

RQ 1. What are the critical success factors that help to deploy lean and sustainable (sustaileanant) innovation for achieving carbon neutrality in supply chains?

RQ 2. How do the identified critical success factors of sustaileanant innovations influence carbon neutrality achievement in manufacturing supply chains?

This research attempts to answer these questions to expand the theoretical and managerial horizons on how lean and sustainable innovations can help achieve net-zero emissions within the Indian manufacturing supply chain and logistics. To this effort, we propose to utilize a two-stage approach comprising strong ordering data envelopment analysis (SODEA) followed by machine learning (ML) based Bayesian network (BN) methods. Initially, we conducted a systematic literature review to understand the crux of lean and sustainable (sustaileanant) innovations for gaining net-zero emissions in the supply chain. Thereafter, we identified the critical success factors (CSFs) that will act as rigid support for organizations to transform their supply chain and logistics to achieve net-zero emissions. Using a validity survey, the identified CSFs are validated for the study. This resulted in the finalization of 14 CSFs falling under 3 major categories. Further, we utilize SODEA to determine the most crucial CSFs by determining their priority weights. We then utilized BN to predict the impact of different CSFs on the level of net-zero emission achieved. Finally, a sensitivity analysis is performed to identify the robustness of the model and determine the most influential CSFs.

The remainder of the paper is structured as follows – Section 2 highlights the comprehensive review of literature on net-zero emissions in the supply chain and the critical success factors of lean and sustainable innovations. Section 3 provides the overall research flow and describes the research methods used for this study. The results are discussed in detail in Section 4. The implications of the research are provided in Section 5. Concluding remarks, research implications, and directions to conduct future research are provided in Section 6.

2 Literature Review

The United Nations Sustainable Development Goal (SDG) has declared the ever-happening climate change driven by excessive anthropogenic carbon emissions as one of the most pressing challenges for humanity (UN, 2015). Carbon neutrality, also known as net-zero emission, is a new milestone for organizations to reach in the present era. It remains unclear whether a state of net-zero emission is possible. If so, how can carbon-dominated production systems and supply chains be transformed toward carbon neutrality? As the industrial sector transitions towards a carbon-neutral practice and works towards achieving net-zero emissions, it is imperative that supply chains play a central role in these efforts. Hence, addressing the carbon footprint of global supply chains is crucial in the pursuit of net-zero emissions. Organizations and governments worldwide are increasingly recognizing the need to adopt sustainable practices, optimize logistics, reduce waste, and transition to cleaner energy sources to mitigate the environmental impact of supply chains (Cao et al., 2023; Ghadge et al., 2020).

2.1 Net-Zero in Manufacturing Supply Chains

The concept of a carbon-neutral supply chain has gained increasing attention in recent years as organizations strive to address the urgent need to mitigate climate change (Mishra et al., 2022). According to the United Nations, net zero is “cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests, for instance” (UN, 2022). Industrial logistic networks contribute extensively to the emissions from various supply chain stages, such as raw material extraction, manufacturing, transportation, and end-of-life disposal. The global supply chain contributes to a significant portion of the world's carbon footprint. While it is challenging to determine an exact percentage, studies indicate that the carbon emissions associated with global supply chains are substantial (Vimal et al., 2022). According to a report by Accenture, global supply chains are responsible for up to 60% of the world's greenhouse gas emissions (Timmermans, 2023). Global institutions are competing with each other to build a more carbon-neutral environment. The University of California announced “Carbon Neutrality” as their most ambitious program (Forgie and Carlson, 2018), and the Paris Government set a goal to transform into a carbon-neutral city by 2050 (Horowitz, 2016). Also, manufacturing organisations adopt programs such as the Science Based Targets initiative and the Carbon Disclosure Project (CDP)¹ to usher towards a net-zero emission economy (de Sousa Jabbour et al., 2019).

¹ <https://www.cdp.net/en/investor/engage-with-companies/cdp-science-based-targets-campaign>

A net-zero emission or carbon neutrality in the manufacturing supply chain aims to minimize or offset the greenhouse gas emissions associated with the entire supply chain network, including the production, transportation, and disposal of goods. The concept of a net-zero or carbon-neutral supply chain involves measuring, reducing, and offsetting carbon emissions throughout the supply chain network (Dohale et al., 2024; Seuring and Müller, 2008; Sindhvani et al., 2022). Numerous studies have examined strategies for reducing carbon emissions in supply chains. These strategies include – 1) Improving energy efficiency within the supply chain to reduce carbon emissions (Bai et al., 2022; Zhu et al., 2011); 2) Shifting towards low-carbon transportation modes, such as electric vehicles or alternative fuels, has been identified as a key strategy for achieving carbon neutrality in supply chains (Hohenstein et al., 2015; Li et al., 2023); 3) Collaborating with suppliers to engage in environmental initiatives, foster knowledge sharing, and develop sustainable practices plays a crucial role in achieving carbon neutrality (Chen et al., 2004; Khan et al., 2022; Naranjo et al., 2023); and 4) adoption of renewable energy sources, such as solar or wind power, within supply chain operations can also contribute to achieving carbon neutrality (Birasnav et al., 2022; Christopher et al., 2023). In adopting and implementing these strategies, collaboration among all stakeholders, including governments, businesses, and consumers, is essential to drive sustainable practices and reduce the carbon footprint of global supply chains (Dohale et al., 2023c; Khan and Ali, 2022; Naranjo et al., 2023). One of the promising approaches to achieving these goals is implementing lean and sustainable innovations that can bring a net-zero economy (Bhattacharya et al., 2019).

2.2 Lean and Sustainable Innovations for Carbon Neutrality

The urgency to address climate change has led to a growing recognition of the need for innovative solutions that can drive the transition to a low-carbon economy. In pursuing carbon neutrality, organizations increasingly turn to lean and sustainable innovation practices to reduce emissions and create more environmentally responsible operations (Bhattacharya et al., 2019; Kumar and Mathiyazhagan, 2020). Lean innovations² rooted in the principles of lean thinking and continuous improvement are acting as a promising approach that has gained traction in recent years for developing and implementing strategies to achieve net-zero emissions (Bag, 2023; Ladhadd and Parrish, 2013; Wu and Feng, 2012). While traditional approaches to innovation focus primarily on technological advancements, lean innovation

² <https://fourprinciples.com/expert-opinion/how-lean-digital-supports-companies-in-achieving-net-zero-supply-chains/>

encompasses a broader perspective. It emphasizes the elimination of waste, the optimization of processes, and the continuous search for efficiency in all aspects of an organization's operations (Farias et al., 2019; Naranjo et al., 2023; Netland, 2016; Rötzer et al., 2016).

On the other hand, when lean innovations are combined with a focus on sustainability, i.e. sustaileanant innovations, they offer a powerful framework to address environmental concerns and achieve carbon neutrality encompassing the advantages of both lean and sustainable practises (Cherrafi et al., 2018; Debnath et al., 2023; Hartini and Ciptomulyono, 2015). Thus, the potential pathways can be constructed through deploying lean, green and digital innovation to rearrange the value chain for decarbonization. Figure 1 demonstrates the benefits of sustaileanant innovations towards achieving net-zero emissions.

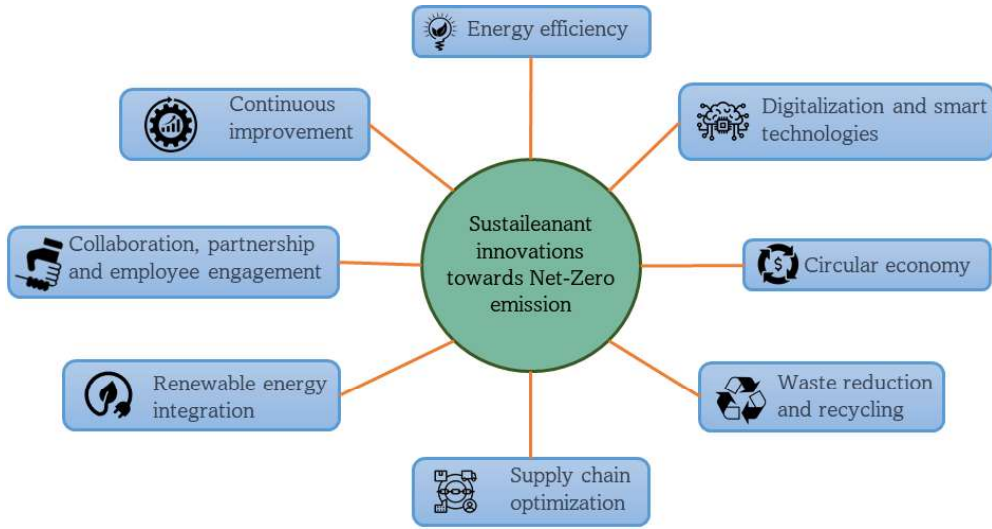


Figure 1. Sustaileanant Innovations for Net-Zero emissions

It has been witnessed that many industries are adopting zero-emission approaches by utilizing sustaileanant innovative solutions to mitigate environmental hazards by reducing greenhouse gas (GHG) emissions. Leading fashion brands, namely – Reformation, Kirkwood, and Allbirds, are becoming carbon-positive and are certified carbon-neutral organizations (VOGUE, 2021). Allbirds, a leading shoe manufacturer, created an innovative product medication by using natural materials like sugarcane-based sweet foam to make carbon-neutral shoes (Allbirds, 2022). The most noticeable and appreciable fact of this innovation is that Allbirds made this innovation accessible to its competitors as well to make the entire industry more sustainable (Hobson and Hagan, 2019). Apart from this, organizations are using sustaileanant thinking and approach in their supply chains to gain a carbon-neutral tag. Some of the notable mentions are as follows –

- Unilever, an international consumer goods company, has embraced lean and sustainable practices to achieve carbon neutrality. The company's Sustainable Living Plan includes ambitious goals, such as sourcing 100% of agricultural raw materials sustainably and becoming carbon-positive in its operations by 2030. Unilever has implemented various initiatives to optimize its supply chain, including reducing transportation distances, improving energy efficiency, and collaborating with suppliers to promote sustainable practices (Unilever, 2021).
- Interface, a global flooring manufacturer, has demonstrated how lean and sustainable innovation can drive carbon neutrality. The company's "Mission Zero" commitment focuses on eliminating negative environmental impacts. By adopting lean principles, such as waste elimination and energy efficiency improvements, the interface significantly reduced energy consumption and carbon emissions (Luqmani et al., 2017; UN, 2021).
- Patagonia, an outdoor clothing and gear company, integrates lean innovation with sustainable practices throughout its supply chain. Patagonia focuses on sourcing recycled and environmentally friendly materials, reducing water and energy consumption in manufacturing, and promoting the repair and reuse of products to extend their lifecycle. By incorporating sustainable principles into its operations, such as efficient inventory management and streamlined distribution processes, Patagonia reduces emissions associated with transportation (Alonso, 2023; Bateman and Bonanni, 2019; Patagonia, 2023).

Although effective in achieving sustainability and reducing carbon footprints, these approaches, i.e. sustainable practices, incur additional costs to organizations and burden the supply chains and overall business strategies (Mahapatra et al., 2021). These costs make organizations resist the strategic implementation of such initiatives. Thus, efforts are needed from organizations to transform their mindset to achieve carbon-neutral operations in the supply chain. Despite that, in their recent review, de Sousa Jabbour et al. (2019) and Mishra et al. (2022) highlighted the urgent need for research on zero-emission or carbon neutrality in the supply chain. The current studies on carbon neutrality consider a macro perspective and undertake carbon neutrality at the global, regional, and national levels by focusing on policy and technological aspects (Chen et al., 2022; Sandberg and Krook-Riekkola, 2022; Zhang et al., 2022). Sandberg and Krook-Riekkola (2022) highlighted the need to conduct quantitative studies in a net-zero industrial context. Some studies have analysed the drivers and barriers of circular economy and carbon neutrality (Dohale et al., 2023b; Kannan et al., 2022; Sindhvani

et al., 2022; Zhang et al., 2022). Although effective in helping implement net-zero initiatives in the supply chain, research on sustainable innovations and their critical success factors for carbon neutrality is nascent. While the strength of these determinants may vary from sector to sector, the Indian manufacturing sector represents a revelatory application case for this study due to its significant carbon footprint. CO₂ emissions from the Indian manufacturing sector in 2014³ were reported as 26.4%. Hence, it shows an extraordinary potential for improvement toward net-zero emissions.

2.3 Research Gaps

Based on the extensive literature review conducted in this study, it is imperative that implementing sustainable innovations in the manufacturing supply chains will have great potential to achieve net-zero goals. However, it is essential to develop a foundationary work that can guide this implementation. We identified several research gaps in the extant literature as follows -

RG 1. Most of the literature discusses different lean and sustainable innovations for circular economy and sustainability separately (Orji and Liu, 2020; Qureshi et al., 2022; Schot and Geels, 2008), but fewer efforts are put into identifying the combined role of sustainable innovations in achieving net-zero goals.

RG 2. The literature is sparse in determining and consolidating the critical success factors of Sustainable innovations towards net-zero achievement.

RG 3. Literature lacks to evaluate and interpret the strength of sustainable innovation to achieve net-zero targets.

3 Research Methodology

3.1 Research Paradigm and Design

Research paradigm, a fundamental step of establishing a philosophical stance (Hegde, 2015; Remenyi et al., 1998), is developed within a scientific discipline as a guiding perspective for a researcher to know what to study, how the study will be carried out, and which suitable methods to utilise (Bryman and Bell, 2015). The research paradigms are categorised as – positivism, realism, interpretivism and pragmatism (Saunders et al., 2009). The present research work is developed within the vicinity of the pragmatism research paradigm, a research stance which focuses on the problem under observation to establish a solution by collecting different

³ <https://knoema.com/atlas/India/topics/Environment/Emissions/CO2-emissions-from-manufacturing-industries-percent>

perspectives to help interpret the data and derive knowledge about the problem (Saunders et al., 2020; Shali, 1986; Yunus and Yang, 2012). The research question is the fundamental determinant of the pragmatic stance (Saunders et al., 2009). As a research paradigm, pragmatism offers legitimacy to use mixed methods of qualitative and quantitative nature in a single study to answer research questions (Yunus and Yang, 2012). Based on the pragmatism paradigm, this study utilises a mixed-method research design, consisting of a systematic literature review, strong ordering data envelopment analysis (SODEA) and Bayesian network (BN) methods to address the RGs and evaluate the CSFs of sustaileanant innovations to achieve net-zero emission in Indian manufacturing supply chains. Initially, the CSFs for sustaileanant innovation are identified through a systematic literature review and validated through experts using a validity survey. The detailed research framework to conduct the current study is presented in Figure 2. In the following section, we described the SODEA and BN methods.

3.2 Identification of CSFs of Sustaileanant Innovation

A systematic literature review (SLR) is carried out to identify the critical success factors (CSFs) of sustaileanant innovations to achieve net-zero targets within the supply chain of manufacturing organizations. We investigated the pertinent literature thoroughly to identify relevant research articles over the major academic databases, including – Scopus, web of science, and EBSCOhost, iteratively. We searched two keyword clusters – 1) related to sustaileanant innovations for carbon neutrality, such as – "net-zero", "carbon neutrality", "carbon neutral", "net zero", "climate neutrality", "decarbonization", "lean", "green practices", "sustainable practices", "innovations"; and 2) related to CSFs as "factors", "determinants", "enablers", "critical success factors", "critical factors", etc. in the title/abstract/keywords field.

The keyword clusters are combined using Boolean operators (AND/OR). Keywords from the same clusters are combined using OR operator, while the different cluster keywords are coupled with AND operator. The initial search produced a sample of 576 relevant articles. Further, articles having duplication, not aligning with the scope, erratum, notes, corrigendum, or written in a language other than English are excluded. We only included articles published in peer-reviewed journals from 2016 onwards (i.e. within a span of 5-7 years) to have relevance in the current era. This resulted in the final sample of 32 research articles used for conducting this study and identifying suitable CSFs. These 32 research articles discuss the domain of study in depth and help to build the foundation of this study.

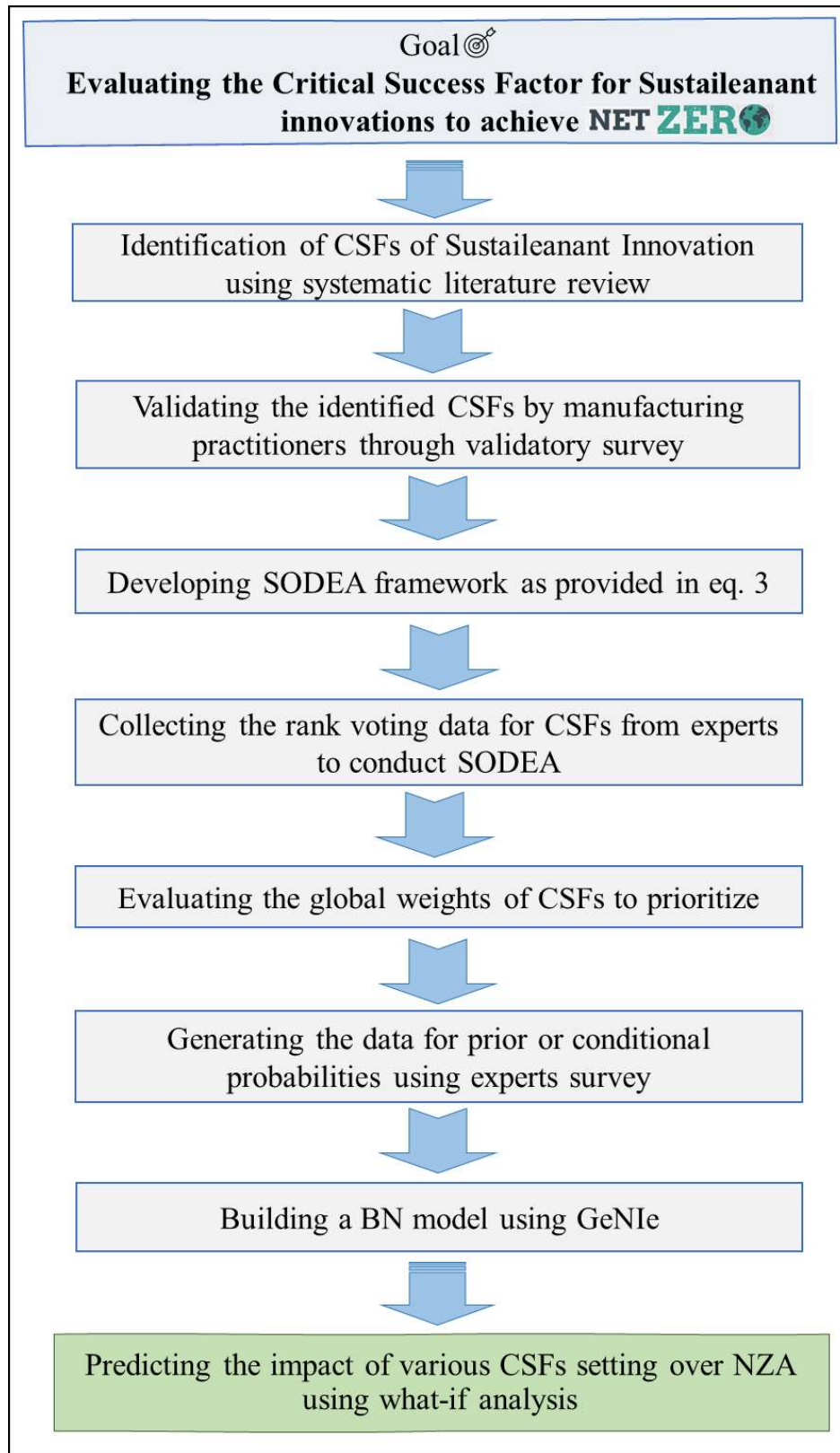


Figure 2. Research Approach

Further, digging down into those 32 articles, we determined that 15 articles have highlighted the list of critical success factors. The detailed procedure to carry-out SLR is illustrated in Figure 3. We analysed the list of CSFs provided in the 15 articles. Reading the definitions of the CSFs and understanding their meanings, we arrived at 14 unique CSFs that cover both lean and sustainability philosophies., which fall under 3 major groups.

We then used a validity survey method to check the relevance and reliability of the 14 identified CSFs for the study's context, i.e., the Indian manufacturing supply chain, using industrial experts' opinions. We initially contacted 196 experts to validate the identified CSFs. Out of these, 125 experts showed interest and participated in the validity survey. Further, all 125 experts responded to the complete questionnaire of the validity survey. This depicts a response rate of 64%. It is reported in the existing literature that a response rate of > 20% is adequate for gaining valuable insights into the problem through surveyed data (Dohale et al., 2024; Majumdar et al., 2021; Malhotra and Grover, 1998). The profile of participants and detailed questionnaire for validity survey are provided in Appendix 1 and 2, respectively. The experts were asked to assign scores to the identified CSFs based on their relevance using the five-point Likert scale (Strongly Disagree = 1; Strongly agree = 5). CSFs obtaining a mean score of ≥ 3.0 are retained for the study (Dohale et al., 2023b; Majumdar et al., 2021). The responses of the validity survey are provided in Appendix 3. All 14 CSFs falling under 3 groups, i.e. managerial, Governmental and legal, and technical factors, are validated by experts. The description of all CSFs is provided in Appendix 4.

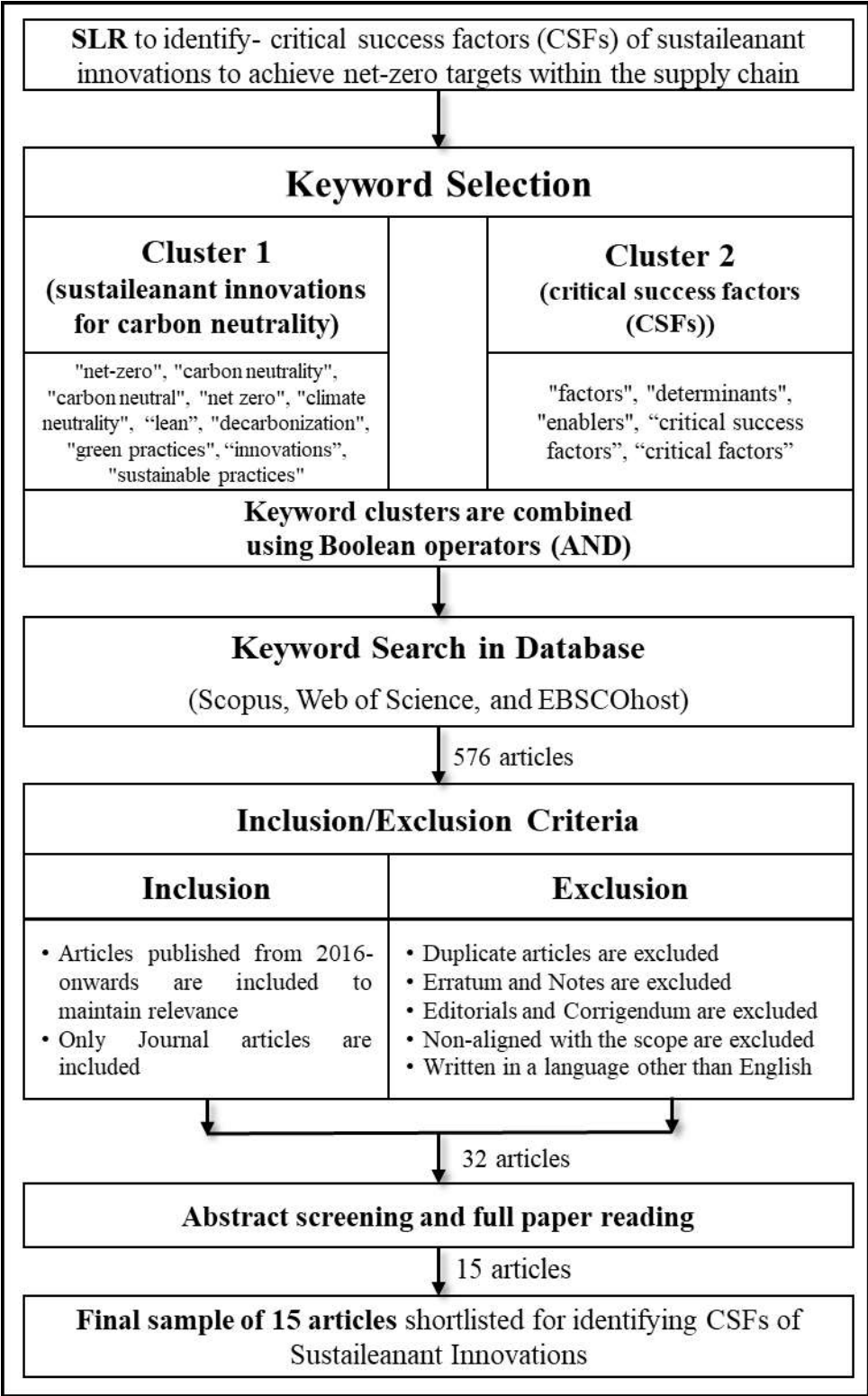


Figure 3. Stepwise procedure for SLR

Table 1. Critical Success Factors of Sustainable Innovations for Net-Zero Achievement

Sr No.	#CSF	Critical Success Factors	References*														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CSF1 Managerial Factors																	
1	CSF11	Adequate support from top management in the implementation process	✓	✓		✓	✓			✓		✓	✓	✓	✓	✓	✓
2	CSF12	Availability of funds for implementation of sustainable practices		✓		✓	✓			✓		✓	✓				
3	CSF13	Collaboration among stakeholders				✓											
4	CSF14	Availability of Professional Expertise	✓	✓	✓		✓			✓		✓				✓	✓
5	CSF15	Focus on research and development activities to advent innovative technological solutions							✓					✓			
CSF2 Governmental and Legal Factors																	
6	CSF21	Incentive schemes for organization		✓		✓					✓	✓	✓			✓	
7	CSF22	Promoting sustainability & CO2 Emission reduction initiatives				✓							✓				
8	CSF23	Strategic planning and effective roadmap	✓				✓		✓	✓			✓	✓			✓
9	CSF24	Law and Certification				✓					✓	✓					
CSF3 Technical Factors																	
10	CSF31	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	✓		✓				✓				✓				
11	CSF32	Maintaining sustainability in waste management		✓	✓		✓						✓			✓	
12	CSF33	Carbon footprint reduction														✓	✓
13	CSF34	Adoption of eco-innovation for achieving Net-zero target			✓			✓		✓		✓			✓		
14	CSF35	Availability of sustainable supplier		✓			✓			✓		✓	✓	✓	✓	✓	✓

***References:** 1 - (Netland, 2016), 2 - (Thanki and Thakkar, 2018) 3 - (Zhan et al., 2018), 4 - (de Sousa Jabbour et al., 2019), 5 - (de la Vega et al., 2020), 6 - (Kumar et al., 2020), 7 - (Tripathi et al., 2021), 8 - (Wu et al., 2021), 9 - (Asmae et al., 2022), 10 - (Fleith de Medeiros et al., 2022), 11 - (Mathiyazhagan et al., 2022), 12 - (Qureshi et al., 2022), 13 - (Virmani et al., 2022), 14 - (Debnath et al., 2023), 15 - (Mohib et al., 2023)

3.3 Strong Ordering Data Envelopment Analysis

SO-DEA is one of the most popular methods to rank the attributes by computing the weighted sum of the votes received by each attribute and determining their priority weights. SO-DEA, also known as the voting analytical hierarchy process (VAHP), is used to solve multi-criteria decision-making problems (Hadi-Vencheh and Niazi-Motlagh, 2011; Liu and Hai, 2005). Liu and Hai (2005) first utilized SO-DEA based VAHP, a modified version of AHP, to evaluate the suitable supplier (Pishchulov et al., 2019; Sipahi and Timor, 2010). The roots of SO-DEA were found in the 1990s. In the seminal work, Cook and Kress proposed a DEA-based procedure which helps rank the candidates in a preferential election (Cook and Kress, 1990). Each of the voters, based on their preferences, ranks the candidates at different places as - 1st, 2nd, 3rd, ..., Sth place.

Further, Green, Doyle, and Cook (1996) modified this model, referred to as ‘‘Green’s method’’ in which authors set constraints to weights. Green’s method comprises two sub-methods to set constraints: (1) the difference of weights between consecutive places, i.e., Sth place and (S+1)th place, is allowed to be zero; (2) The difference of weights between consecutive places must be strictly more than zero. Assume that there are R criteria for ranking. Let there be n voters (respondents). Each voter assigns the weight u_{rs} to maximize the weighted sum of the votes to r^{th} criteria at s^{th} place, where the weighted sum is represented by θ_{rr} . The first set of constraints proposed by Green et al. (1996) is termed as ‘‘Green’s Weak Ordering’’ method, which is represented as –

$$\left. \begin{aligned} \theta_{rr} &= \max \sum_{s=1}^S u_{rs} x_{rs} \\ \text{Subjected to, } \theta_{rp} &= \sum_{s=1}^S u_{rs} x_{rp} \leq 1 \quad (p = 1, 2, \dots, R) \\ u_{r1} - u_{r2} &\geq u_{r2} - u_{r3} \geq \dots \geq u_{rS-1} - u_{rS} \geq d(S-1, \varepsilon) \geq 0 \\ u_{r1} &\geq u_{r2} \geq u_{r3} \geq \dots \geq u_{rS} \geq 0 \end{aligned} \right\} \quad (1)$$

Where, $d(S-1, \varepsilon)$ in equation (1) is the discriminating intensity function that denotes the gap between S^{th} versus $(S+1)^{\text{th}}$, and ε denotes the discriminating factor. The second method by Green et al. (1996), in which weights between consecutive places are kept more than zero, is known as ‘‘Green’s Strong Ordering Method’’ and represented as –

$$\begin{aligned}
& \theta_{rr} = \max \sum_{s=1}^S u_{rs} x_{rs} \\
& \text{Subjected to, } \theta_{rp} = \sum_{s=1}^S u_{rs} x_{rp} \leq 1 \quad (p = 1, 2, \dots, R) \\
& u_{r1} - u_{r2} \geq u_{r2} - u_{r3} \geq \dots \geq u_{rS} - Su_{rS} \geq d(S, \varepsilon) = \varepsilon \geq 0 \\
& u_{r1} \geq u_{r2} \geq u_{r3} \geq \dots \geq u_{rS} \geq \varepsilon
\end{aligned} \tag{2}$$

Here, x_{rs} denotes the total number of votes received to the r^{th} criterion given by n voters for s^{th} place. Some numbers will be obtained for x_{r1} as first place, x_{r2} as second place, and x_{rS} for S^{th} place, $r = 1, 2, \dots, R$; $s = 1, 2, \dots, S$; and $d(S, \varepsilon) = \varepsilon$ appearing in the aforementioned equation (2) signifies the difference in weights between S^{th} and $(S+1)^{\text{th}}$ place. However, Green's method comprises certain shortcomings as – (a) application to concrete examples and (b) total ranking changes with change in ε value.

Later, Noguchi et al. (2002) developed a strong ordering method to tackle the shortcomings of Green's method. Moreover, Noguchi's strong ordering method effectively evaluates single and multi-purpose problems (Hadi-Vencheh and Niazi-Motlagh, 2011; Hai and Liu, 2007). In the total ranking method using DEA, "Noguchi's strong ordering" is given as:

$$\begin{aligned}
& \theta_{rr} = \max \sum_{s=1}^S u_{rs} x_{rs} \\
& \text{Subjected to, } \theta_{rp} = \sum_{s=1}^S u_{rs} x_{rp} \leq 1 \quad (p = 1, 2, \dots, R) \\
& u_{r1} \geq 2u_{r2} \geq 3u_{r3} \geq \dots \geq Su_{rS} \\
& u_{rS} \geq \varepsilon \\
& \varepsilon \geq \frac{2}{n \times S(S+1)}
\end{aligned} \tag{3}$$

Noguchi's strong ordering method is the basis for calculating the weights of attributes using the SO-DEA method (Ayyildiz and Taskin Gumus, 2021; Dohale et al., 2023a; Liu and Hai, 2005). The weights are evaluated from rank voting data along with the SO-DEA method (Azadeh et al., 2009; Soltanifar and Hosseinzadeh Lotfi, 2011). In this work, we propose to utilize the SO-DEA model for evaluating the priority weights of CSFs.

The rationale for using SO-DEA over other popular multi-criteria decision-making (MCDM) methods is due to its benefits, as given below:

- SO-DEA uses a linear programming formulation, making it mathematically sound, unlike many MCDM methods (Soltanifar and Hosseinzadeh Lotfi, 2011).
- SO-DEA is easy to understand and provides equal opportunity to all the experts for voting and assessing the reasonableness of ranking (Azadeh et al., 2009; Dohale et al., 2021).
- SO-DEA has no restriction over the number of experts, unlike other MCDM methods. In SO-DEA, experts can vary from 8 to more than 100 (Ayyildiz and Taskin Gumus, 2021; Dohale et al., 2021).
- SO-DEA has no restriction over the number of attributes. Typically, in many MCDM methods, there are limitations for the criteria under evaluation, such as 9 criteria in the best-worst method or AHP/ANP (Rezaei, 2015; Saaty, 2008).

Since the purpose of the research is to uncover novel insights and the influence of CSFs of sustainable innovations for NZA in an exploratory manner, it is desirable to have inputs from multiple experts. As SODEA outperforms well compared to any other MCDM in capturing the data from multiple experts and analyzing it mathematically, it has been selected as most appropriate for the present study.

Deployment of the appropriate voters or respondents with adequate expertise plays a vital role as the results rely on the experts' know-how. Hence, we utilized four critical expert selection criteria to retain suitable respondents/voters – i) Since the research is related to the manufacturing industry, experts shall be from a manufacturing background; ii) knowledge about carbon neutrality and its associated activities; iii) Experience of at least five years in the area of net-zero or carbon emission reduction, green, lean, and sustainable practices in the manufacturing industry; and iv) Enthusiasm to participate in the study (Bokrantz et al., 2017; Dohale et al., 2021).

Initially, we contacted 207 manufacturing experts. Further, we checked whether a particular expert is equipped with at least five years in the area of net-zero or carbon emission reduction, green, lean, and sustainable practices (as mentioned in criteria 2) to ensure the suitability of a particular respondent for the study. Thus, based on all four criteria, 125 respondents out of 207 from Indian manufacturing industries were shortlisted for conducting the SODEA procedure. These 125 experts are the same as validity surveys, making the responses consistent. The

ranking data is collected from the 125 shortlisted voters for all the CSFs (respondents). The questionnaire for collecting ranking data for SODEA is provided in Appendix 5. Whereas the ranking data is shown in Table 2. The SODEA model shown in equation 3 is used to compute the priority weights using the ranking data.

Table 2. Rank Voting Data for CSFs of sustaileanant practices

Group CSF	1st Place	2nd Place	3rd Place
CSF1	71	26	28
CSF2	78	16	31
CSF3	81	31	13

Managerial	1st Place	2nd Place	3rd Place	4th Place	5th Place
CSF11	24	36	34	31	0
CSF12	26	39	29	24	7
CSF13	24	34	16	29	22
CSF14	32	31	29	19	14
CSF15	21	13	24	22	45

G and L	1st Place	2nd Place	3rd Place	4th Place
CSF21	118	5	2	0
CSF22	101	21	3	0
CSF23	94	16	7	8
CSF24	99	19	4	3

Technical	1st Place	2nd Place	3rd Place	4th Place	5th Place
CSF31	78	34	13	0	0
CSF32	76	29	20	0	0
CSF33	86	34	5	0	0
CSF34	81	29	15	0	0
CSF35	69	28	22	6	0

3.4 Bayesian Network

BN is one of the most powerful predictive ML-based statistical operation tools used for complex decision-making (Hosseini et al., 2020). Researchers have predominantly used BN for solving intricate problems consisting of uncertainty (Hosseini et al., 2020; Hosseini and Barker, 2016a; Kaya et al., 2023). BN follows Bayes's theorem and is based on statistical learning theory (Castillo et al., 1997). BN graphically shows the probabilistic interlinks

between the attributes (Wuest et al., 2016). In BN, the directed acyclic graphs (DAG) are used to model the probabilistic interdependencies between the two attributes, viz. variables, factors, risks, etc. DAG consists of various nodes connected through arcs. The attributes are represented through nodes, while the probabilistic dependencies between attributes are shown using the arcs (Hosseini et al., 2020; Hosseini and Ivanov, 2021). A Conditioned Probability Table (CPT) or Node Probability Table (NPT) is assigned to every node to define the conditional probabilities of the attribute.

BN possesses certain additive benefits over other ML techniques, such as – i) BN evaluates attributes with a qualitative and quantitative nature; ii) Even with limited data, BN effectively solves the problem under study; iii) It provides an ability of rigorous learning; and 4) The outputs of BN are easily understood and interpretable (Dohale et al., 2022a; Hosseini and Sarder, 2019). BN can capture the strength of interrelationships more efficiently than the other graphical approaches, namely, social network analysis, DEMATEL, and interpretive structural modelling (ISM) (Kamble et al., 2021). Furthermore, BN can effectively conduct what-if analysis to understand the impact of change in the probability of parent or input node attributes over the output or target node (Dohale et al., 2024; Hosseini and Barker, 2016a). As the study focuses on determining the influence of each CSF of sustainable innovation on NZA, it is required to have a predictive analytical model. Since qualitative data through a survey needs to be collected from experts, and BN handles such data effectively, it has been considered to be a suitable method for the present research work.

In this study, we evaluated and predicted the impact of CSFs of sustainable innovations on the achievement of carbon neutrality and determined the most influential CSFs. In this study, the target or output node is set as the net-zero achievement, while the 14 CSFs are the input nodes, and the 3 group CSFs are the intermediate nodes. In BN, the prior probabilities of input nodes are used as data to develop a problem. The data for prior probabilities of nodes can be retained through system-generated real data or expert surveys (Dohale et al., 2022a; Wuest et al., 2016).

We utilized a method proposed by Dohale et al. (2022) for collecting the prior probability data. In this research, the data for the prior probabilities of the input nodes, i.e., 14 CSFs, is collected through a survey using the shortlisted 125 respondents deployed for a validity survey and SODEA. Having similar experts in all methods helps to achieve homogeneity in opinions. The survey comprises questions related to the influence of CSFs on the achievement of net-zero emissions in supply chains. For example, experts are asked the question– "According to you,

what level of influence does 'Professional Expertise (CSF14)' have in the net-zero achievement in manufacturing supply chains?" The experts provided their responses over a six-point Likert scale (1 – Extremely Low (EL); 2 – Very Low (VL); 3 – Low (L); 4 – High (H); 5 – Very High (VH); 6 – Extremely High (EH). The experts' responses were classified into two categories – Low (L, VL, and EL) and High (H, VH, and EH). The survey questionnaire and its responses for generating prior probabilistic data of BN are provided in Appendix 6 and 7.

Based on the experts' responses, the probabilities of the influence of CSFs were determined into the Low and High categories. For example, the responses received for 'professional expertise (CSF14)' CSF are – 14 (EH), 91 (VH), 16 (H), 4 (L), and 0 for both (VL) and (EL). This implies that 121 (14+91+16) out of 125 experts prefer high values while the remaining 4 prefer low values. Thus, the probabilities of high and low values are computed as: $\left(\frac{121}{125}\right) = 0.968$ and $\left(\frac{4}{125}\right) = 0.032$, respectively. Similarly, the prior probabilities of all the other CSFs are computed in high and low categories. The prior probabilities are used to develop a BN model. In this study, we deployed the GeNIe package, one of the most utilized software for building the BN model. Ease of working in the GeNIe platform, handling complex problems with a large volume of data, and the ability to generate precise results are the forte and noteworthy advantages of GeNIe. The BN model developed in GeNIe is shown in Figure 4.

4 Results and Discussions

The results obtained through SODEA and Bayesian network methods are discussed in detail in this section.

4.1 Results from SODEA

The SODEA model shown in equation 3 is used to compute the relative weights of CSFs of sustaileanant innovations for achieving carbon neutrality using weights using the ranking data provided in Table 2. The weight calculations ae presented in Table 3. The CSFs are then prioritized according to their global weights, as highlighted in Table 3. The results achieved through SODEA uncover some critical and interesting findings. In the group factors, almost every CSF has received the same weight with a marginal difference. Technical (CSF3) and Govt. and Legal (CSF 2) factors have gained more weight than managerial (C1). Technical know-how is crucial in implementing strategic decisions and practices (Dohale et al., 2023b; Zou et al., 2021). Whereas managerial factors are critical in implementing and brainstorming unique ideas for net-zero achievement.

One of the prime KPIs of managers in manufacturing industries has been achieving the desired sustainability targets and carbon-neutral goals (Dohale et al., 2022c; Sindhvani et al., 2022). However, in most cases, organizations possess the required understanding but lack appropriate management strategies for driving decarbonization through their operations and supply chains. Hence, managers must be equipped with adequate professional expertise about the skills required to monitor the implementation of sustainable practices to achieve net-zero targets (de Sousa Jabbour et al., 2019; Netland, 2016; Virmani et al., 2022). The results achieved through SODEA also validated this statement as, in terms of sub-CSFs within managerial factors (CSF1), availability of professional expertise (CSF14) ranked 1 with a global weight of 0.0693. Apart from this, the availability of the sufficient amount of funds required for investing in sustainable innovations to achieve net zero emission strategies are crucial. Until adequate funds are available, implementing decarbonization initiatives will be on a toss. Manufacturing practitioners can seek help from the Government as a funding body to obtain subsidies for moving toward these initiatives.

Table 3. Weight Calculation of Sustainable CSFs

Group CSFs	Relative weight of group CSFs	Normalized weight of group CSFs (Wg)	Sub CSFs	Relative weights of Sub-CSFs	Normalized weight of sub-CSFs (Ws)	Global Weights (Wg × Ws)
CSF1	0.9256	0.3208	CSF11	0.9792	0.2114	0.0678
			CSF12	0.9842	0.2125	0.0682
			CSF13	0.8960	0.1934	0.0620
			CSF14	1.0000	0.2159	0.0693
			CSF15	0.7726	0.1668	0.0535
CSF2	0.9599	0.3327	CSF21	1.0000	0.2689	0.0895
			CSF22	0.9285	0.2497	0.0831
			CSF23	0.8776	0.2360	0.0785
			CSF24	0.9127	0.2454	0.0816
CSF3	1.0000	0.3466	CSF31	0.9490	0.2013	0.0698
			CSF32	0.9283	0.1969	0.0682
			CSF33	1.0000	0.2121	0.0735
			CSF34	0.9602	0.2036	0.0706
			CSF35	0.8774	0.1861	0.0645

Manufacturers have a restricted view about implementing sustainable innovations in their operations and supply chains for net-zero achievement due to the additional cost incurred in it

(Sindhwani et al., 2022). Thus, the incentivization from the Governmental can encourage manufacturing professionals to adopt sustainable innovations for bringing carbon-neutral supply chains. Apart from this, an awareness campaign about the sustainability and CO₂ reduction initiatives to achieve net-zero emissions and their benefits to the industry through its implementation can help practitioners gain more profound knowledge (Dohale et al., 2023c; Sindhwani et al., 2022). The role of the Government in taking legal provisions and communicating and imposing different sustainability initiatives is crucial in achieving these carbon-neutral goals (Muthu, 2019; Sindhwani et al., 2022). Legal certifications are crucial drivers and facilitators of green supply chain initiatives (Dohale et al., 2023c; Govindan et al., 2016). It has been observed that once policies are converted into mandatory laws, manufacturers feel pushed to substantially transform their activities in line with net-zero targets (Govindan et al., 2016; Majumdar and Sinha, 2019; Sindhwani et al., 2022).

Lean, Green and sustainable practices (LGSPs) involve innovative environment-friendly techniques within the operations and supply chain (Bhattacharya et al., 2019), which can help achieve a sector's overall sustainable development goals (Nyangchak, 2022; Oelze, 2017; Wang and Zhao, 2022). However, adequate knowledge of the available sustainable and lean tools and techniques to achieve net-zero goals is a fundamental requirement. Adopting eco-innovative sustainable mechanisms is another way of achieving carbon neutrality (Fleith de Medeiros et al., 2022; Virmani et al., 2022). Global manufacturing organizations are seeking new technological interventions, particularly Industry 5.0. Industry 5.0 is conceived as more sustainable and resilient⁴, where interactive human-machine platforms can develop (Ghobakhloo et al., 2022). Since industry 5.0 is more man-machine-centric, it can help resolve the issue of fear of unemployment. Industries worldwide are collaborating to develop sustainable ways to overcome the issues of carbon dominance in the manufacturing industry. Organizations to reduce their carbon footprints passionately work on developing methods that help scrap carbon dioxide off. Carbon offsetting is one such eco-innovative that deals with *"processes of compensating for carbon dioxide emissions arising from industrial or other human activity by participating in schemes designed to make equivalent reductions of carbon dioxide in the atmosphere"* (Rayer et al., 2022).

⁴https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/industry-50-towards-more-sustainable-resilient-and-human-centric-industry-2021-01-07_en

4.2 Bayesian Network and Sensitivity analysis

We utilized BN to determine the influence of each of the CSFs of sustainable innovations on the overall achievement of net-zero goals with the supply chain of the manufacturing industry. We conducted a what-if analysis in GeNIe to compute the impact of the different CSF settings on the NZA. Figure 4 shows a BN model for one of the possible combinations of CSFs and the achieved probabilistic NZA – High = 0.86 and Low = 0.14. We computed the NZA with the various settings of CSFs and enlisted in Table 4. To get a more explicit understanding of the influential CSFs, we conducted a “strength of influence” analysis of CSFs using GeNIe. The result of the analysis is shown in Figure 5. The strength of influence diagram of CSFs shown in Figure 5 depicts incentive schemes for organizations (CSF21), availability of professional expertise (CSF14), availability of funds for implementing sustainable practices (CSF12), maintaining sustainability in waste management (CSF32), carbon footprint reduction (CSF33), and know-how of sustainable tools and techniques (CSF31), are the most influential and shows a significant impact on NZA in the manufacturing industry. The finding of the influence diagram supports the results obtained from SODEA.

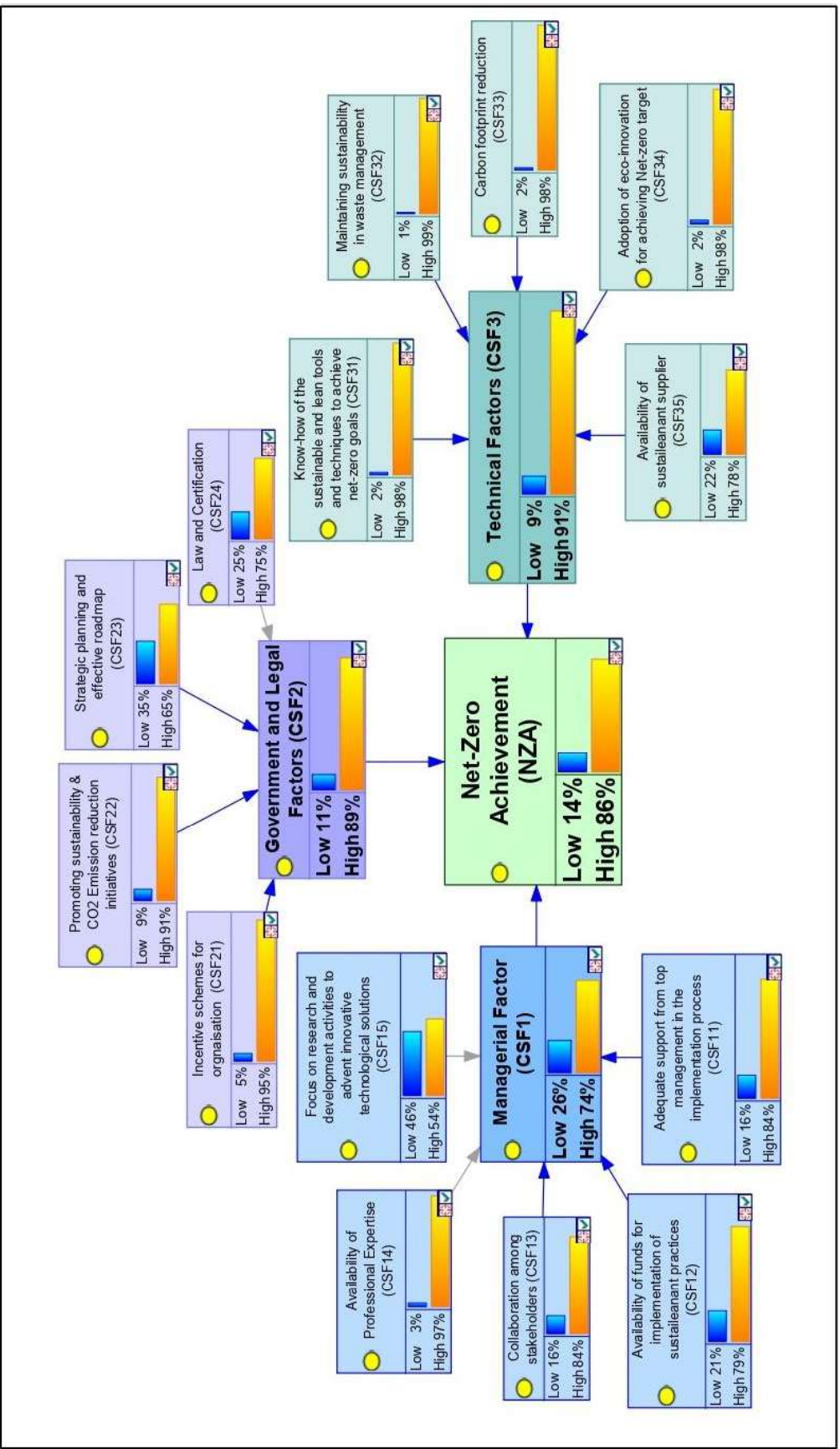


Figure 4. Bayesian Network for the NAZ analysis

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Table 4. Impact of conditional probabilities of CSFs over NZA

24	Managerial (CSF1)					CSF1		Govt. and Legal (CSF2)				CSF2		Technical (CSF3)					CSF3		Net-Zero Achievement (NZA)								
	CSF11	CSF12	CSF13	CSF14	CSF15	L	H	CSF21	CSF22	CSF23	CSF24	L	H	CSF31	CSF32	CSF33	CSF34	CSF35	L	H	CSF1	CSF2	CSF3	L	H	L	H		
	L	L	L	L	L	0.999	0.001	L	L	L	L	0.990	0.010	L	L	L	L	L	1.000	0.000	L	L	L	0.900	0.100	L	L	1.000	0.000
26L	L	L	L	L	L	0.980	0.020	L	L	L	L	0.900	0.100	L	L	L	L	L	0.900	0.100	L	L	L	0.900	0.100	L	L	0.930	0.070
27L	L	L	L	L	L	0.950	0.050	L	L	L	L	0.850	0.150	L	L	L	L	L	0.850	0.150	L	L	L	0.950	0.050	L	L	0.750	0.250
28L	L	L	L	L	L	0.945	0.055	L	L	L	L	0.850	0.150	L	L	L	L	L	0.850	0.150	L	L	L	0.950	0.050	L	L	0.350	0.650
29L	L	L	L	L	L	0.935	0.065	L	L	L	L	0.950	0.050	L	L	L	L	L	0.950	0.050	L	L	L	0.930	0.070	L	L	0.750	0.250
30L	L	L	L	L	L	0.600	0.400	L	L	L	L	0.950	0.050	L	L	L	L	L	0.600	0.400	L	L	L	0.600	0.400	L	L	0.205	0.795
31L	L	L	L	L	L	0.800	0.200	L	L	L	L	0.800	0.200	L	L	L	L	L	0.800	0.200	L	L	L	0.800	0.200	L	L	0.000	1.000
32L	L	L	L	L	L	0.570	0.430	L	L	L	L	0.800	0.200	L	L	L	L	L	0.570	0.430	L	L	L	0.570	0.430	L	L	0.000	1.000
33L	L	L	L	L	L	0.920	0.080	L	L	L	L	0.550	0.450	L	L	L	L	L	0.920	0.080	L	L	L	0.920	0.080	L	L	0.000	1.000
34L	L	L	L	L	L	0.725	0.275	L	L	L	L	0.550	0.450	L	L	L	L	L	0.730	0.270	L	L	L	0.730	0.270	L	L	0.000	1.000
35L	L	L	L	L	L	0.650	0.350	L	L	L	L	0.050	0.950	L	L	L	L	L	0.650	0.350	L	L	L	0.650	0.350	L	L	0.000	1.000
36L	L	L	L	L	L	0.695	0.305	L	L	L	L	0.050	0.950	L	L	L	L	L	0.700	0.300	L	L	L	0.700	0.300	L	L	0.000	1.000
37L	L	L	L	L	L	0.650	0.350	L	L	L	L	0.150	0.850	L	L	L	L	L	0.650	0.350	L	L	L	0.650	0.350	L	L	0.000	1.000
38L	L	L	L	L	L	0.175	0.825	L	L	L	L	0.150	0.850	L	L	L	L	L	0.170	0.830	L	L	L	0.170	0.830	L	L	0.000	1.000
39L	L	L	L	L	L	0.550	0.450	L	L	L	L	1.000	0.000	L	L	L	L	L	0.550	0.450	L	L	L	0.550	0.450	L	L	0.000	1.000
40L	L	L	L	L	L	0.150	0.850	L	L	L	L	1.000	0.000	L	L	L	L	L	0.150	0.850	L	L	L	0.150	0.850	L	L	0.000	1.000
41L	L	L	L	L	L	0.800	0.200	L	L	L	L	0.800	0.200	L	L	L	L	L	0.800	0.200	L	L	L	0.800	0.200	L	L	0.000	1.000
42H	L	L	L	L	L	0.750	0.250	L	L	L	L	0.750	0.250	L	L	L	L	L	0.750	0.250	L	L	L	0.750	0.250	L	L	0.000	1.000
43H	L	L	L	L	L	0.825	0.175	L	L	L	L	0.825	0.175	L	L	L	L	L	0.820	0.180	L	L	L	0.820	0.180	L	L	0.000	1.000
44H	L	L	L	L	L	0.715	0.285	L	L	L	L	0.715	0.285	L	L	L	L	L	0.720	0.280	L	L	L	0.720	0.280	L	L	0.000	1.000
45H	L	L	L	L	L	0.700	0.300	L	L	L	L	0.700	0.300	L	L	L	L	L	0.700	0.300	L	L	L	0.700	0.300	L	L	0.000	1.000
46H	L	L	L	L	L	0.350	0.650	L	L	L	L	0.350	0.650	L	L	L	L	L	0.350	0.650	L	L	L	0.350	0.650	L	L	0.000	1.000
47H	L	L	L	L	L	0.625	0.375	L	L	L	L	0.625	0.375	L	L	L	L	L	0.630	0.370	L	L	L	0.630	0.370	L	L	0.000	1.000
48H	L	L	L	L	L	0.075	0.925	L	L	L	L	0.075	0.925	L	L	L	L	L	0.070	0.930	L	L	L	0.070	0.930	L	L	0.000	1.000
49H	L	L	L	L	L	0.550	0.450	L	L	L	L	0.550	0.450	L	L	L	L	L	0.550	0.450	L	L	L	0.550	0.450	L	L	0.000	1.000
50H	L	L	L	L	L	0.515	0.485	L	L	L	L	0.515	0.485	L	L	L	L	L	0.520	0.480	L	L	L	0.520	0.480	L	L	0.000	1.000
51H	L	L	L	L	L	0.550	0.450	L	L	L	L	0.550	0.450	L	L	L	L	L	0.550	0.450	L	L	L	0.550	0.450	L	L	0.000	1.000
52H	L	L	L	L	L	0.275	0.725	L	L	L	L	0.275	0.725	L	L	L	L	L	0.270	0.730	L	L	L	0.270	0.730	L	L	0.000	1.000
53H	L	L	L	L	L	0.345	0.655	L	L	L	L	0.345	0.655	L	L	L	L	L	0.340	0.660	L	L	L	0.340	0.660	L	L	0.000	1.000
54H	L	L	L	L	L	0.195	0.805	L	L	L	L	0.195	0.805	L	L	L	L	L	0.200	0.800	L	L	L	0.200	0.800	L	L	0.000	1.000
55H	L	L	L	L	L	0.325	0.675	L	L	L	L	0.325	0.675	L	L	L	L	L	0.320	0.680	L	L	L	0.320	0.680	L	L	0.000	1.000
56H	L	L	L	L	L	0.999	0.001	L	L	L	L	0.999	0.001	L	L	L	L	L	1.000	0.000	L	L	L	1.000	0.000	L	L	0.000	1.000

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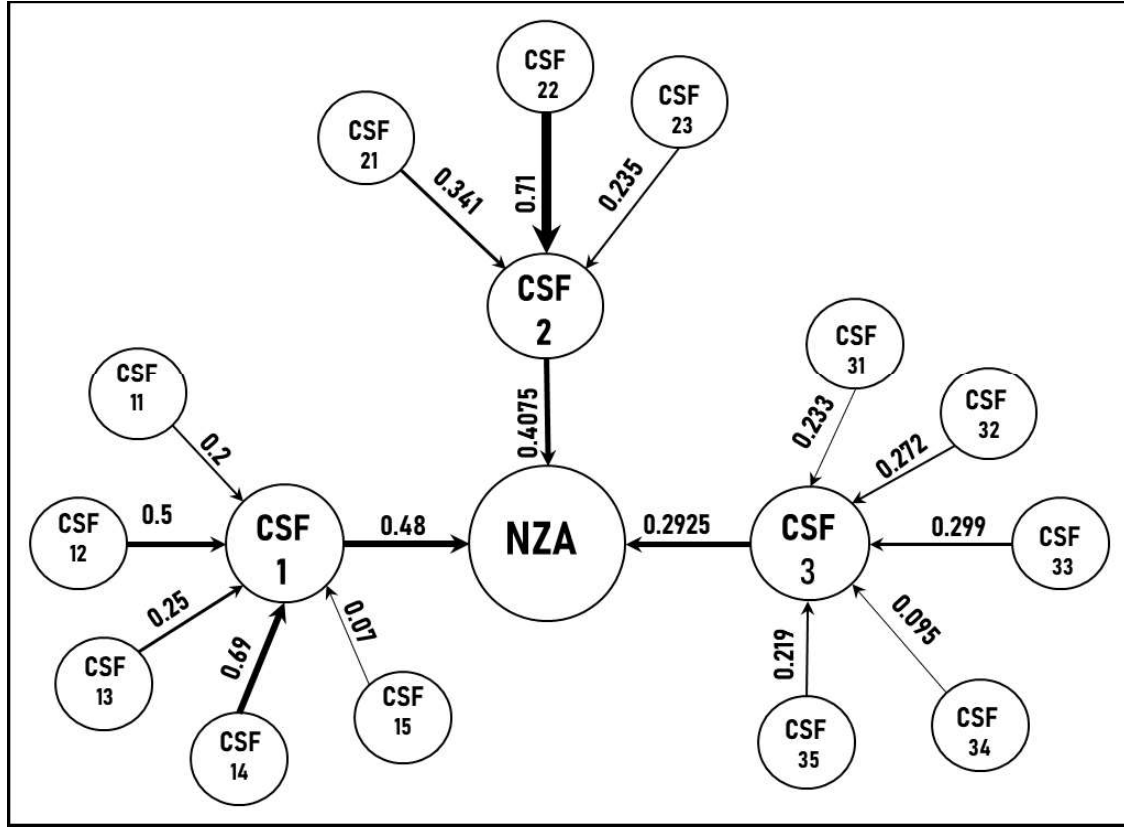


Figure 5. Strength Influence Diagram

Furthermore, to validate the robustness of the model and the results obtained through the proposed BN, we conducted a sensitivity analysis. Sensitivity analysis is the most suitable and practical approach that helps validate expert-built BN models (Dohale et al., 2021; Hosseini and Sarder, 2019). In sensitivity analysis, the assessment of the variation that occurred in the model's outcome with the changes in input parameters is captured (Hosseini and Barker, 2016a). The influential attributes within the model can be easily identified and analysed using sensitivity analysis. Sensitivity analysis also validates whether the model can be replicated in future research or not (Dohale et al., 2022a; Hosseini and Barker, 2016b).

GeNIe has an in-built feature to conduct the sensitivity analysis and offers the results in a Tornado graph (GeNIe, 2022). This study quantifies the impact of 14 CSFs under 3 group CSFs on the achievement of net-zero emission in Indian manufacturing supply chains. Thus, in this model, the 14 CSFs are the sensitive nodes to check their influence over the target node, i.e., NZA. The sensitivity analysis results are shown through the tornado graph in Figure 6. Each bar represents the CSFs considered in this study. The bar length indicates the influence of determinants over the target node, i.e. NZA (GeNIe, 2022). As evident from Figure 6, incentive schemes for organizations (CSF21), availability of professional expertise (CSF14), and

availability of funds for implementing sustainable practices (CSF12) are the influential CSFs. Findings from SODEA and strength of influence analysis support these results.

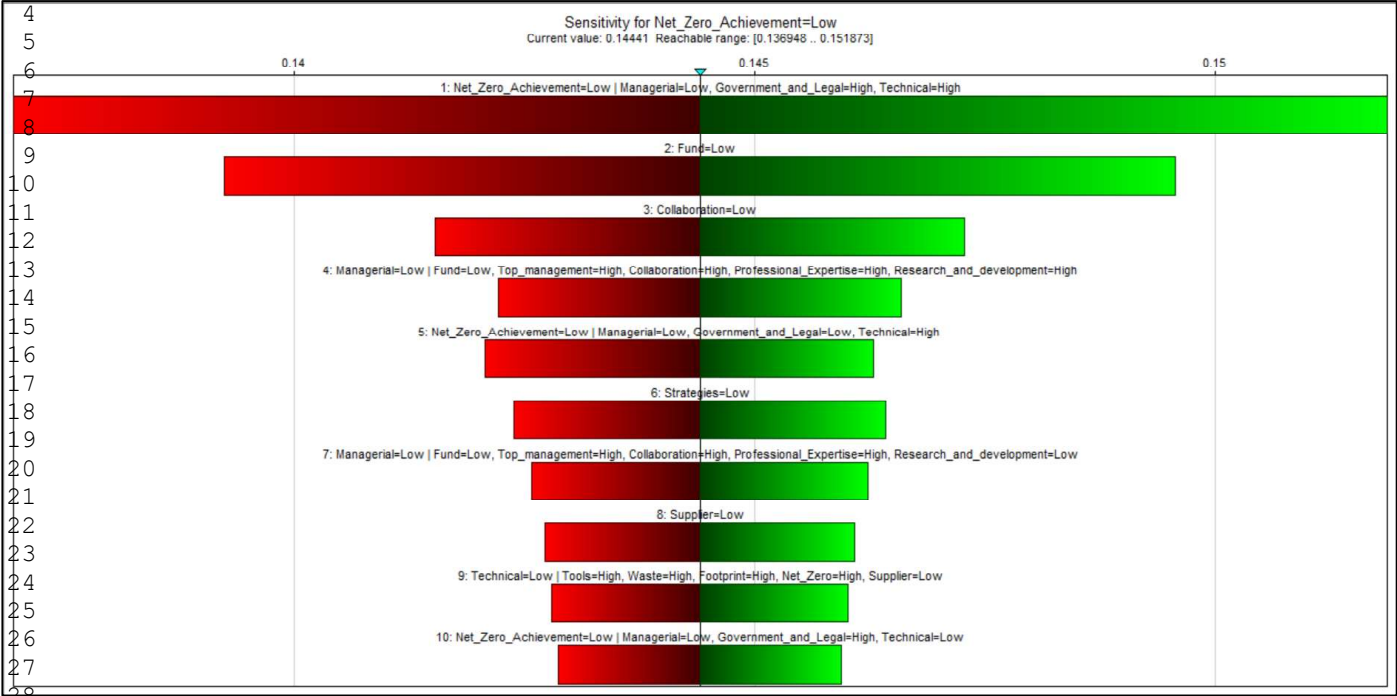


Figure 6. Sensitivity Analysis

5 Implications of the present research

The present research has a significant theoretical implication to the literature on net-zero emission and managerial implications to practitioners within the operations and supply chain domain. The present study complements the body of knowledge in the domain of not only environmental management but also operations and supply chain sustainability. This study offers novel insights into the CSFs of sustainable innovations that help for net-zero achievement in the context of the Indian manufacturing supply chains through a quantitative methodological approach. This study has noteworthy theoretical and methodological contributions to the state-of-the-art literature. Despite the criticality of sustainable innovations for NZA in supply chains, the literature on carbon neutrality and supply chain is still in its infancy to determine the critical factors to implement the sustainable innovations. The present study has made an early attempt in the literature to fill this gap. This study has successfully evaluated the influence of different CSFs of sustainable innovations over carbon neutrality achievement. Apart from this, a notable methodological contribution to the operations research literature is the application of the two-stage SODEA and BN methodology.

Existing studies have proved that combining ML techniques with optimization and MCDM methods strengthens the computation and helps overcome the shortcomings within one method (Dohale et al., 2022a; Kaya et al., 2023). Thus, the proposed SODEA and BN can effectively handle intricate problems with a big dataset and extend to other large-scale problems.

Alike its theoretical relevance, this study also offers practical implications. This study can be a guideline for manufacturing practitioners who are willing to implement sustainable innovation to engage with carbon-neutral supply chains. Managers may foster the key and significant CSFs in their organizations in a targeted manner to successfully execute and achieve decarbonization and net-zero emission practices within their operations and supply chains. Manufacturers can collaborate with each other to invent new sustainable innovations in line with NZA and make them available to their competitors, similar to Allbirds (Allbirds, 2022; Hobson and Hagan, 2019). Practitioners who are already engaged with sustainable innovations for NZA can utilize this study to compare the NZA achieved at their organizations with the present study's findings. This will help them comprehend the possible improvements in influential CSFs for attaining an optimal NZA. We also postulate that this research work can be insightful to practitioners to achieve operational excellence more generally through the interventions of sustainable innovations and practices in their operations and supply chain.

Apart from these implications, the present work has some recommendations in line with the sustainable development goals (SDGs). United nations defined SDGs as – “*the blueprint to achieve a better and more sustainable future for all*” (UN, 2020). The merging of SDGs and the pursuit of NZA carries significant ramifications within the manufacturing supply chain (Sofuoğlu and Kirikkaleli, 2022). Sustainable innovations are pivotal in steering manufacturing supply chains in striving towards the attainment of NZE and align closely with several SDGs, notably SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Organizations can significantly reduce their environmental footprint by integrating cleaner technologies, renewable energy sources, and eco-friendly materials (Ikram et al., 2021; Yadav et al., 2023). Complementing these efforts, embracing lean principles further bolsters these initiatives by optimizing resource utilization, minimizing waste, and enhancing operational efficiency.

Strategies encompassing digitalization, collaborative partnerships, and stringent carbon neutrality targets are also instrumental (Chauhan et al., 2022; Ma et al., 2024). In parallel, education, policy reinforcement, and a culture of continuous improvement form the bedrock

for nurturing a sustainable ethos across supply chains. This convergence of strategies propels advancements toward net-zero and fosters responsible production and consumption aligned with the SDGs (Cai and Choi, 2020; Gunawan et al., 2020; Yadav et al., 2023). By strategically aligning sustainable practices with the SDGs, the manufacturing supply chain addresses environmental concerns, drives economic growth, and cultivates social development. The infusion of sustainability in combination with lean (sustainable) into manufacturing supply chains significantly contributes to global endeavours to achieve net-zero emissions, steering us closer to a universally sustainable future.

6 Conclusion and Future Research Directions

The increment in manufacturing carbon footprint is becoming a nightmare for manufacturers as it is damaging not only the environment but also humanity presently and in the coming future. The goal to achieve “Carbon neutrality by 2050” has become the world's most urgent mission (Wang et al., 2021). Many nations have actively participated in this ambitious initiative of the United Nations to transform to carbon neutral by 2050. Governmental institutions are encouraging manufacturing industries to passionately work towards this agenda. Manufacturers are making their best efforts to reform their operations and supply chain in line with net-zero emissions. Different strategies have been conceived that help to achieve net-zero emissions. One such promising approach involves adopting sustainable and lean (sustainable) innovation that gives a boost to industries by delivering the benefits of both. Despite this fact, academia and practitioners are still stagnated to implement sustainable innovations in their business and supply chain level that can help them usher towards net-zero targets.

This research investigates and analyses the critical success factors that help manufacturers implement sustainable innovations to achieve carbon-neutral operations and supply chains. To this purpose, this study made an effort to answer the research questions mentioned in Section 1. We conducted a systematic literature review to address RQ 1, followed by a validity survey. We reviewed relevant literature to determine the essence of lean and sustainable innovations in the achievement of carbon-neutral supply chains and also presented some industrial examples to get a clearer understanding of the concept. Further, we identified 14 CSFs falling under 3 group CSFs that can help manufacturers implement sustainable innovations and convert their conventional operations and supply chain in a carbon-neutral manner. We also validated these 14 CSFs by utilizing the expertise of 125 manufacturing practitioners using a validity survey.

We adopted a two-stage approach comprising SODEA and BN methods to address RQ2. We evaluated all CSFs using these methods. Through SODEA, we determined the most crucial CSFs to implement sustainable innovations by computing their priority weights. Whereas BN is used to evaluate and predict the influence of each CSF on the overall net-zero achievement in Indian manufacturing supply chains. The findings from both methods complement each other. The results depict that incentive schemes for the organization (CSF21), availability of professional expertise (CSF14), and availability of funds for implementing sustainable practices (CSF12) are the key CSFs that show a significant level of influence on NZA. These CSFs are the ones in which manufacturing organizations can retain core competencies to achieve net-zero emissions in their operations and supply chains. Thus, embracing sustainable innovation by considering the significant CSFs for its implementation can enable businesses not only to reduce their carbon footprint but also to strengthen their competitiveness in the global market.

We propose a few directions for conducting future research. This study pertains to the analysis of CSFs in the manufacturing industry. However, a manufacturing industry can be spread across many environments, including – textile, automotive, plastic, machining, chemical, metal fabrication, etc. We expect that the findings may vary from environment to environment. Thus, prospective researchers can conduct future research to target a specific manufacturing environment and evaluate how these CSFs can influence the NZA. One of the most noticeable trade-offs observed in recent days is between the resilience and sustainability aspects within supply chains. The COVID-19 or the Suez Canal incident are the unanticipated disruptive events that occurred recently, which triggered the prominence of resilience in supply chains (Dohale et al., 2022b). Thus, researchers can rethink the Sustainable (sustainable + resilient) approach that can cater not only for sustainability but also for resilience in supply chains to develop resilient carbon neutrality within the operations and supply chains (Ambilkar et al., 2023; Dohale et al., 2023d). We further propose a technology adoption-based framework to understand how these sustainable innovations can play a mediating role in achieving net-zero targets by their successful adoption in various industries across different countries. Future studies can conduct a techno-economic analysis of the identified determinants of sustainable innovations of NZA to analyse the economic performance of manufacturing processes, products, or services.

Acknowledgement

We are immensely grateful to all the participating respondents who spent their time and efforts providing their opinions to us, which were instrumental in conducting this research work. We are also thankful to the anonymous reviewers and editors for providing their valuable feedback to help improve the quality of this research.

References

- Allbirds, 2022. We're changing so the climate doesn't [WWW Document]. URL <https://www.allbirds.com/pages/our-commitment> (accessed 4.13.22).
- Alonso, T., 2023. How Patagonia Became The Benchmark In Sustainable Clothing [WWW Document]. Strateg. Fact. by Cascade. URL <https://www.cascade.app/studies/patagonia-strategy-study>
- Ambilkar, P., Dohale, V., Gunasekaran, A., Bilollikar, V., 2022. Product returns management: a comprehensive review and future research agenda. *Int. J. Prod. Res.* 60, 3920–3944. <https://doi.org/10.1080/00207543.2021.1933645>
- Ambilkar, P., Verma, P., Das, D., 2023. Sustailient supplier selection using neutrosophic best–worst approach: a case study of additively manufactured trinkets. *Benchmarking An Int. J.* <https://doi.org/10.1108/BIJ-02-2023-0122>
- Asmae, M., Abdelali, E.-N., Brahim, H., 2022. Critical success factors of Lean implementation in Moroccan agro food supply chain, in: 2022 14th International Colloquium of Logistics and Supply Chain Management (LOGISTIQUA). IEEE, pp. 1–6. <https://doi.org/10.1109/LOGISTIQUA55056.2022.9938121>
- Ayyildiz, E., Taskin Gumus, A., 2021. A novel distance learning ergonomics checklist and risk evaluation methodology: A case of Covid- 19 pandemic. *Hum. Factors Ergon. Manuf. Serv. Ind.* 31, 397–411. <https://doi.org/10.1002/hfm.20908>
- Azadeh, A., Keramati, A., Songhori, M.J., 2009. An integrated Delphi/VAHP/DEA framework for evaluation of information technology/information system (IT/IS) investments. *Int. J. Adv. Manuf. Technol.* 45, 1233–1251. <https://doi.org/10.1007/s00170-009-2047-2>
- Bag, S., 2023. From resources to sustainability: a practice-based view of net zero economy implementation in small and medium business-to-business firms. *Benchmarking An Int. J.* <https://doi.org/10.1108/BIJ-01-2023-0056>
- Bai, C., Zhu, Q., Sarkis, J., 2022. Supplier portfolio selection and order allocation under carbon neutrality: Introducing a “Cool”ing model. *Comput. Ind. Eng.* 170, 108335. <https://doi.org/10.1016/j.cie.2022.108335>
- Bateman, A., Bonanni, L., 2019. What Supply Chain Transparency Really Means. *Harv. Bus. Rev.* 2–8.

- 1 Bhattacharya, A., Nand, A., Castka, P., 2019. Lean-green integration and its impact on
2 sustainability performance: A critical review. *J. Clean. Prod.* 236, 117697.
3 <https://doi.org/10.1016/j.jclepro.2019.117697>
- 4 Birasnav, M., Chaudhary, R., Henry Dunne, J., Bienstock, J., Seaman, C., 2022. Green supply
5 chain management: A theoretical framework and research directions. *Comput. Ind. Eng.*
6 172, 108441. <https://doi.org/10.1016/j.cie.2022.108441>
- 7
8
9 Bokrantz, J., Skoogh, A., Berlin, C., Stahre, J., 2017. Maintenance in digitalised
10 manufacturing : Delphi-based scenarios for 2030. *Int. J. Prod. Econ.* 191, 154–169.
11 <https://doi.org/10.1016/j.ijpe.2017.06.010>
- 12
13
14 Bryman, A., Bell, E., 2015. *Business Research Methods*, 4th Edn. ed. Oxford University Press,
15 New York.
- 16
17 Cai, Y.-J., Choi, T.-M., 2020. A United Nations’ Sustainable Development Goals perspective
18 for sustainable textile and apparel supply chain management. *Transp. Res. Part E Logist.*
19 *Transp. Rev.* 141, 102010. <https://doi.org/10.1016/j.tre.2020.102010>
- 20
21
22 Cao, K., Guo, Q., Xu, Y., 2023. Information sharing and carbon reduction strategies with
23 extreme weather in the platform economy. *Int. J. Prod. Econ.* 255, 108683.
24 <https://doi.org/10.1016/j.ijpe.2022.108683>
- 25
26
27 Castillo, E., Gutiérrez, J.M., Hadi, A.S., 1997. *Expert Systems and Probabilistic Network*
28 *Models, Monographs in Computer Science.* Springer New York, New York, NY.
29 <https://doi.org/10.1007/978-1-4612-2270-5>
- 30
31
32 Chauhan, C., Kaur, P., Arrawatia, R., Ractham, P., Dhir, A., 2022. Supply chain collaboration
33 and sustainable development goals (SDGs). Teamwork makes achieving SDGs dream
34 work. *J. Bus. Res.* 147, 290–307. <https://doi.org/10.1016/j.jbusres.2022.03.044>
- 35
36
37 Chen, I.J., Paulraj, A., Lado, A.A., 2004. Strategic purchasing, supply management, and firm
38 performance. *J. Oper. Manag.* 22, 505–523. <https://doi.org/10.1016/j.jom.2004.06.002>
- 39
40
41 Chen, L., Msigwa, G., Yang, M., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.-S., 2022.
42 Strategies to achieve a carbon neutral society: a review. *Environ. Chem. Lett.* 20, 2277–
43 2310. <https://doi.org/10.1007/s10311-022-01435-8>
- 44
45
46 Cherrafi, A., Garza-Reyes, J.A., Kumar, V., Mishra, N., Ghobadian, A., Elfezazi, S., 2018.
47 Lean, green practices and process innovation: A model for green supply chain
48 performance. *Int. J. Prod. Econ.* 206, 79–92. <https://doi.org/10.1016/j.ijpe.2018.09.031>
- 49
50
51 Christopher, S., Vikram, M.P., Bakli, C., Thakur, A.K., Ma, Y., Ma, Z., Xu, H., Cuce, P.M.,
52 Cuce, E., Singh, P., 2023. Renewable energy potential towards attainment of net-zero
53 energy buildings status – A critical review. *J. Clean. Prod.* 405, 136942.
54 <https://doi.org/10.1016/j.jclepro.2023.136942>
- 55
56
57 Cook, W.D., Kress, M., 1990. A Data Envelopment Model for Aggregating Preference
58 Rankings. *Manage. Sci.* 36, 1302–1310. <https://doi.org/10.1287/mnsc.36.11.1302>
- 59
60
61 COP26, 2021. The Glasgow climate pact. UN Climate Change Conference UK 2021, Glasgow,
62 UK., in: *Cop26: The Glasgow Climate Pact*.

- de la Vega, M., Baez-Lopez, Y., Limon-Romero, J., Tlapa, D., Flores, D.L., Rodríguez Borbón, M.I., Maldonado-Macías, A.A., 2020. Lean manufacturing critical success factors for the transportation equipment manufacturing industry in Mexico. *IEEE Access* 8, 168534–168545. <https://doi.org/10.1109/ACCESS.2020.3023633>
- de Sousa Jabbour, A.B.L., Chiappetta Jabbour, C.J., Sarkis, J., Gunasekaran, A., Furlan Matos Alves, M.W., Ribeiro, D.A., 2019. Decarbonisation of operations management – looking back, moving forward: a review and implications for the production research community. *Int. J. Prod. Res.* 57, 4743–4765. <https://doi.org/10.1080/00207543.2017.1421790>
- Debnath, B., Shakur, M.S., Bari, A.B.M.M., Karmaker, C.L., 2023. A Bayesian Best–Worst approach for assessing the critical success factors in sustainable lean manufacturing. *Decis. Anal. J.* 6. <https://doi.org/10.1016/j.dajour.2022.100157>
- Dellink, R., Hwangi, H., Lanzi, E., Chateau, J., 2017. International trade consequences of climate change (No. 2017/01), OECD Trade and Environment Working Papers. <https://doi.org/10.1787/9f446180-en>
- Dohale, V., Akarte, M., Gunasekaran, A., Verma, P., 2022a. Exploring the role of artificial intelligence in building production resilience: learnings from the COVID-19 pandemic. *Int. J. Prod. Res.* 1–17. <https://doi.org/10.1080/00207543.2022.2127961>
- Dohale, V., Akarte, M.M., Gunasekaran, A., Verma, P., 2023a. Quantifying and Exhibiting the Congruence of Process Choice Criteria with Traditional and Additive Manufacturing Systems. *Prod. Plan. Control* 1–25.
- Dohale, V., Ambilkar, P., Bilollikar, V., Narkhede, B.E., Kumar, Ashwani, Kumar, Anil, 2023b. Evaluating circular economy and smart technology adoption barriers in the Indian textile and apparel industries using neutrosophic ISM. *Ann. Oper. Res.* <https://doi.org/10.1007/s10479-023-05651-5>
- Dohale, V., Ambilkar, P., Gunasekaran, A., Verma, P., 2022b. Supply chain risk mitigation strategies during COVID-19: exploratory cases of “make-to-order” handloom saree apparel industries. *Int. J. Phys. Distrib. Logist. Manag.* 52, 109–129. <https://doi.org/10.1108/IJPDLM-12-2020-0450>
- Dohale, V., Ambilkar, P., Kumar, A., Mangla, S.K., Bilollikar, V., 2023c. Analyzing the enablers of circular supply chain using Neutrosophic-ISM method: lessons from the Indian apparel industry. *Int. J. Logist. Manag.* 34, 611–643. <https://doi.org/10.1108/IJLM-03-2022-0141>
- Dohale, V., Gunasekaran, A., Akarte, M., Verma, P., 2021. An integrated Delphi-MCDM-Bayesian Network framework for production system selection. *Int. J. Prod. Econ.* 242, 108296. <https://doi.org/10.1016/j.ijpe.2021.108296>
- Dohale, V., Gunasekaran, A., Akarte, M.M., Verma, P., 2022c. 52 Years of manufacturing strategy: an evolutionary review of literature (1969–2021). *Int. J. Prod. Res.* 60, 569–594. <https://doi.org/10.1080/00207543.2021.1971788>
- Dohale, V., Kamble, S., Ambilkar, P., Gold, S., Belhadi, A., 2024. An integrated MCDM-ML approach for predicting the carbon neutrality index in manufacturing supply chains. *Technol. Forecast. Soc. Change* 201, 123243.

<https://doi.org/10.1016/j.techfore.2024.123243>

- Dohale, V., Verma, P., Gunasekaran, A., Amblikar, P., 2023d. COVID-19 and supply chain risk mitigation: a case study from India. *Int. J. Logist. Manag.* 34, 417–442. <https://doi.org/10.1108/IJLM-04-2021-0197>
- Farias, L.M.S., Santos, L.C., Gohr, C.F., Rocha, L.O., 2019. An ANP-based approach for lean and green performance assessment. *Resour. Conserv. Recycl.* 143, 77–89. <https://doi.org/10.1016/j.resconrec.2018.12.004>
- Fleith de Medeiros, J., Bisognin Garlet, T., Duarte Ribeiro, J.L., Nogueira Cortimiglia, M., 2022. Success factors for environmentally sustainable product innovation: An updated review. *J. Clean. Prod.* 345, 131039. <https://doi.org/10.1016/j.jclepro.2022.131039>
- Forgie, J., Carlson, A., 2018. Overcoming Organizational Barriers to Carbon Neutrality: Lessons from the UC Experience. *POLICY Br.* 9, 1–11.
- General Electric, 2021. Sustainability Report Building a World That Works for Tomorrow.
- GeNIe, 2022. GeNIe Modeler - USER MANUAL [WWW Document]. URL <https://support.bayesfusion.com/docs/GeNIe.pdf>
- Ghadge, A., Wurtmann, H., Seuring, S., 2020. Managing climate change risks in global supply chains: a review and research agenda. *Int. J. Prod. Res.* 58, 44–64. <https://doi.org/10.1080/00207543.2019.1629670>
- Ghobakhloo, M., Iranmanesh, M., Mubarak, M.F., Mubarik, M., Rejeb, A., Nilashi, M., 2022. Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values. *Sustain. Prod. Consum.* 33, 716–737. <https://doi.org/10.1016/j.spc.2022.08.003>
- Govindan, K., Muduli, K., Devika, K., Barve, A., 2016. Investigation of the influential strength of factors on adoption of green supply chain management practices: An Indian mining scenario. *Resour. Conserv. Recycl.* 107, 185–194. <https://doi.org/10.1016/j.resconrec.2015.05.022>
- Green, R.H., Doyle, J.R., Cook, W.D., 1996. Preference voting and project ranking using DEA and cross-evaluation. *Eur. J. Oper. Res.* 90, 461–472. [https://doi.org/10.1016/0377-2217\(95\)00039-9](https://doi.org/10.1016/0377-2217(95)00039-9)
- Gunawan, J., Permatasari, P., Tilt, C., 2020. Sustainable development goal disclosures: Do they support responsible consumption and production? *J. Clean. Prod.* 246, 118989. <https://doi.org/10.1016/j.jclepro.2019.118989>
- Hadi-Vencheh, A., Niazi-Motlagh, M., 2011. An improved voting analytic hierarchy process-data envelopment analysis methodology for suppliers selection. *Int. J. Comput. Integr. Manuf.* 24, 189–197. <https://doi.org/10.1080/0951192X.2011.552528>
- Hai, H.L., Liu, F.-H.F., 2007. Using the total vote-ranking to explore the pairwise comparison method for analytic hierarchy process. *J. Stat. Manag. Syst.* 10, 195–209. <https://doi.org/10.1080/09720510.2007.10701248>

- Hartini, S., Ciptomulyono, U., 2015. The Relationship between Lean and Sustainable Manufacturing on Performance: Literature Review. *Procedia Manuf.* 4, 38–45. <https://doi.org/10.1016/j.promfg.2015.11.012>
- Hegde, D.S. (Ed.), 2015. *Essays on Research Methodology*. Springer India, New Delhi. <https://doi.org/10.1007/978-81-322-2214-9>
- Hobson, J., Hagan, A., 2019. How Allbirds Turned Wool Sneakers into A Billion-Dollar Business [WWW Document]. URL <https://www.wbur.org/hereandnow/2019/09/10/allbirds-tim-brown-wool-sneakers> (accessed 4.14.22).
- Hohenstein, N.-O., Feisel, E., Hartmann, E., Giunipero, L., 2015. Research on the phenomenon of supply chain resilience. *Int. J. Phys. Distrib. Logist. Manag.* 45, 90–117. <https://doi.org/10.1108/IJPDLM-05-2013-0128>
- Horowitz, C.A., 2016. Paris Agreement. *Int. Leg. Mater.* 55, 740–755. <https://doi.org/10.1017/S0020782900004253>
- Hosseini, S., Barker, K., 2016a. A Bayesian network model for resilience-based supplier selection. *Int. J. Prod. Econ.* 180, 68–87. <https://doi.org/10.1016/j.ijpe.2016.07.007>
- Hosseini, S., Barker, K., 2016b. Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports. *Comput. Ind. Eng.* 93, 252–266. <https://doi.org/10.1016/j.cie.2016.01.007>
- Hosseini, S., Ivanov, D., 2021. A multi-layer Bayesian network method for supply chain disruption modelling in the wake of the COVID-19 pandemic. *Int. J. Prod. Res.* <https://doi.org/10.1080/00207543.2021.1953180>
- Hosseini, S., Ivanov, D., Dolgui, A., 2020. Ripple effect modelling of supplier disruption: integrated Markov chain and dynamic Bayesian network approach. *Int. J. Prod. Res.* 58, 3284–3303. <https://doi.org/10.1080/00207543.2019.1661538>
- Hosseini, S., Sarder, M., 2019. Development of a Bayesian network model for optimal site selection of electric vehicle charging station. *Electr. Power Energy Syst.* 105, 110–122. <https://doi.org/10.1016/j.ijepes.2018.08.011>
- Ikram, M., Ferasso, M., Sroufe, R., Zhang, Q., 2021. Assessing green technology indicators for cleaner production and sustainable investments in a developing country context. *J. Clean. Prod.* 322, 129090. <https://doi.org/10.1016/j.jclepro.2021.129090>
- ITF, 2016. The Carbon Footprint of Global Trade [WWW Document]. URL <https://www.itf-oecd.org/sites/default/files/docs/cop-pdf-06.pdf>
- Janssens, C., Havlík, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., Leclère, D., Ohrel, S., Ragnauth, S., Schmid, E., Valin, H., Van Lipzig, N., Maertens, M., 2020. Global hunger and climate change adaptation through international trade. *Nat. Clim. Chang.* 10, 829–835. <https://doi.org/10.1038/s41558-020-0847-4>
- Kamble, S.S., Gunasekaran, A., Kumar, V., Belhadi, A., Foropon, C., 2021. A machine learning based approach for predicting blockchain adoption in supply Chain. *Technol.*

Forecast. Soc. Change 163, 120465. <https://doi.org/10.1016/j.techfore.2020.120465>

Kannan, D., Solanki, R., Kaul, A., Jha, P.C., 2022. Barrier analysis for carbon regulatory environmental policies implementation in manufacturing supply chains to achieve zero carbon. *J. Clean. Prod.* 358, 131910. <https://doi.org/10.1016/j.jclepro.2022.131910>

Kaya, R., Salhi, S., Spiegler, V., 2023. A novel integration of MCDM methods and Bayesian networks: the case of incomplete expert knowledge. *Ann. Oper. Res.* 320, 205–234. <https://doi.org/10.1007/s10479-022-04996-7>

Khan, F., Ali, Y., 2022. Implementation of the circular supply chain management in the pharmaceutical industry. *Environ. Dev. Sustain.* <https://doi.org/10.1007/s10668-021-02007-6>

Khan, S.A.R., Yu, Z., Umar, M., Tanveer, M., 2022. Green capabilities and green purchasing practices: A strategy striving towards sustainable operations. *Bus. Strateg. Environ.* 31, 1719–1729. <https://doi.org/10.1002/bse.2979>

Kumar, N., Mathiyazhagan, K., 2020. Modeling the Interrelationship of Critical Success Factors Adoption of Sustainable Lean Manufacturing Using DEMATEL Approach, in: *Lecture Notes in Mechanical Engineering*, pp. 31–45. https://doi.org/10.1007/978-981-15-1071-7_4

Kumar, N., Mathiyazhagan, K., Mathivathanan, D., 2020. Modelling the interrelationship between factors for adoption of sustainable lean manufacturing: a business case from the Indian automobile industry. *Int. J. Sustain. Eng.* 13, 93–107. <https://doi.org/10.1080/19397038.2019.1706662>

Ladhad, A., Parrish, K., 2013. The role of lean practices for zero net energy retrofits, in: *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*, pp. 855–864.

Li, H., Hao, Y., Xie, C., Han, Y., Wang, Z.-R., 2023. Emerging technologies and policies for carbon-neutral transportation. *Int. J. Transp. Sci. Technol.* 12, 329–334. <https://doi.org/10.1016/j.ijtst.2022.09.002>

Liu, F.-H.F., Hai, H.L., 2005. The voting analytic hierarchy process method for selecting supplier. *Int. J. Prod. Econ.* 97, 308–317. <https://doi.org/10.1016/j.ijpe.2004.09.005>

Luqmani, A., Leach, M., Jesson, D., 2017. Factors behind sustainable business innovation: The case of a global carpet manufacturing company. *Environ. Innov. Soc. Transitions* 24, 94–105. <https://doi.org/10.1016/j.eist.2016.10.007>

Ma, J., Yang, L., Wang, D., Li, Y., Xie, Z., Lv, H., Woo, D., 2024. Digitalization in response to carbon neutrality: Mechanisms, effects and prospects. *Renew. Sustain. Energy Rev.* 191, 114138. <https://doi.org/10.1016/j.rser.2023.114138>

Mahapatra, S.K., Schoenherr, T., Jayaram, J., 2021. An assessment of factors contributing to firms' carbon footprint reduction efforts. *Int. J. Prod. Econ.* 235, 108073. <https://doi.org/10.1016/j.ijpe.2021.108073>

Majumdar, A., Sinha, S.K., 2019. Analyzing the barriers of green textile supply chain

management in Southeast Asia using interpretive structural modeling. *Sustain. Prod. Consum.* 17, 176–187. <https://doi.org/10.1016/j.spc.2018.10.005>

Majumdar, A., Sinha, S.K., Shaw, M., Mathiyazhagan, K., 2021. Analysing the vulnerability of green clothing supply chains in South and Southeast Asia using fuzzy analytic hierarchy process. *Int. J. Prod. Res.* 59, 752–771. <https://doi.org/10.1080/00207543.2019.1708988>

Malhotra, M.K., Grover, V., 1998. An assessment of survey research in POM: from constructs to theory. *J. Oper. Manag.* 16, 407–425. [https://doi.org/10.1016/S0272-6963\(98\)00021-7](https://doi.org/10.1016/S0272-6963(98)00021-7)

Mathiyazhagan, K., Gnanavelbabu, A., Kumar, N., Agarwal, V., 2022. A framework for implementing sustainable lean manufacturing in the electrical and electronics component manufacturing industry: An emerging economies country perspective. *J. Clean. Prod.* 334. <https://doi.org/10.1016/j.jclepro.2021.130169>

Mishra, R., Singh, R., Govindan, K., 2022. Net-zero economy research in the field of supply chain management: a systematic literature review and future research agenda. *Int. J. Logist. Manag.* <https://doi.org/10.1108/IJLM-01-2022-0016>

Mohib, A., En-nadi, A., Herrou, B., 2023. PRIORITISING CRITICAL SUCCESS FACTORS OF LEAN IMPLEMENTATION IN THE FOOD SUPPLY CHAIN. *Proc. Eng. Sci.* 5, 119–132. <https://doi.org/10.24874/pes05.01.012>

Muthu, S.S., 2019. Circular Economy in Textiles and Apparel, Circular Economy in Textiles and Apparel: Processing, Manufacturing, and Design. Elsevier. <https://doi.org/10.1016/C2017-0-03221-4>

Naranjo, F., Menor, L.J., Johnson, P.F., 2023. Lean supply chain management: a contextual contingent reconceptualization and Delphi method study. *Int. J. Oper. Prod. Manag.* <https://doi.org/10.1108/IJOPM-07-2022-0436>

Netland, T.H., 2016. Critical success factors for implementing lean production: The effect of contingencies. *Int. J. Prod. Res.* 54, 2433–2448. <https://doi.org/10.1080/00207543.2015.1096976>

Noguchi, H., Ogawa, M., Ishii, H., 2002. The appropriate total ranking method using DEA for multiple categorized purposes. *J. Comput. Appl. Math.* 146, 155–166. [https://doi.org/10.1016/S0377-0427\(02\)00425-9](https://doi.org/10.1016/S0377-0427(02)00425-9)

Nyangchak, N., 2022. Emerging green industry toward net-zero economy: A systematic review. *J. Clean. Prod.* 378, 134622. <https://doi.org/10.1016/j.jclepro.2022.134622>

Oelze, N., 2017. Sustainable Supply Chain Management Implementation—Enablers and Barriers in the Textile Industry. *Sustainability* 9, 1435. <https://doi.org/10.3390/su9081435>

Orji, I.J., Liu, S., 2020. A dynamic perspective on the key drivers of innovation-led lean approaches to achieve sustainability in manufacturing supply chain. *Int. J. Prod. Econ.* 219, 480–496. <https://doi.org/10.1016/j.ijpe.2018.12.002>

Patagonia, 2023. Everything we make has an impact on the planet [WWW Document]. URL <https://www.patagonia.com/our-footprint/> (accessed 3.20.23).

- Pishchulov, G., Trautrimis, A., Chesney, T., Gold, S., Schwab, L., 2019. The Voting Analytic Hierarchy Process revisited: A revised method with application to sustainable supplier selection. *Int. J. Prod. Econ.* 211, 166–179. <https://doi.org/10.1016/j.ijpe.2019.01.025>
- Qureshi, K.M., Mewada, B.G., Alghamdi, S.Y., Almakayeel, N., Qureshi, M.R.N., Mansour, M., 2022. Accomplishing Sustainability in Manufacturing System for Small and Medium-Sized Enterprises (SMEs) through Lean Implementation. *Sustain.* 14. <https://doi.org/10.3390/su14159732>
- Rayer, Q., Jenkins, S., Walton, P., 2022. Defining Net-Zero and Climate Recommendations for Carbon Offsetting, in: *Business and Policy Solutions to Climate Change*. pp. 13–35. https://doi.org/10.1007/978-3-030-86803-1_2
- Remenyi, D., Williams, B., Money, A., Swartz, E., 1998. *Doing research in business and management: an introduction to process and method*. Sage Publications, London.
- Rezaei, J., 2015. Best-worst multi-criteria decision-making method. *Omega (United Kingdom)* 53, 49–57. <https://doi.org/10.1016/j.omega.2014.11.009>
- Rötzer, S., Wilberg, J., Lindemann, U., 2016. Lean innovation methods: Application & evaluation during a student project, in: *Proceedings of International Design Conference, DESIGN*. pp. 473–482.
- Saaty, T.L., 2008. Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* 1, 83–98.
- Sandberg, E., Krook-Riekkola, A., 2022. The impact of technology availability on the transition to net-zero industry in Sweden. *J. Clean. Prod.* 363, 132594. <https://doi.org/10.1016/j.jclepro.2022.132594>
- Saunders, M.N.K., Lewis, P., Thornhill, A., 2020. *Research Methods for Business Students*, 8th Edn. ed. Pearson, New York, NY, USA.
- Saunders, M.N.K., Lewis, P., Thornhill, A., 2009. *Research Methods for Business Students*. Pearson, New Delhi, India.
- Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technol. Anal. Strateg. Manag.* 20, 537–554. <https://doi.org/10.1080/09537320802292651>
- Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* 16, 1699–1710. <https://doi.org/10.1016/j.jclepro.2008.04.020>
- Shali, D.N., 1986. Pragmatism and Social Interactionism. *Am. Sociol. Rev.* 51, 9–29.
- Sindhwani, R., Singh, P.L., Behl, A., Afridi, M.S., Sammanit, D., Tiwari, A.K., 2022. Modeling the critical success factors of implementing net zero emission (NZE) and promoting resilience and social value creation. *Technol. Forecast. Soc. Change* 181, 121759. <https://doi.org/10.1016/j.techfore.2022.121759>
- Sipahi, S., Timor, M., 2010. The analytic hierarchy process and analytic network process: an

overview of applications. *Manag. Decis.* 48, 775–808.
<https://doi.org/10.1108/00251741011043920>

Sofuoğlu, E., Kirikkaleli, D., 2022. Towards achieving net zero emission targets and sustainable development goals, can long-term material footprint strategies be a useful tool? *Environ. Sci. Pollut. Res.* 30, 26636–26649. <https://doi.org/10.1007/s11356-022-24078-2>

Soltanifar, M., Hosseinzadeh Lotfi, F., 2011. The voting analytic hierarchy process method for discriminating among efficient decision making units in data envelopment analysis. *Comput. Ind. Eng.* 60, 585–592. <https://doi.org/10.1016/j.cie.2010.12.016>

Thanki, S.J., Thakkar, J., 2018. Interdependence analysis of lean-green implementation challenges: a case of Indian SMEs. *J. Manuf. Technol. Manag.* 29, 295–328. <https://doi.org/10.1108/JMTM-04-2017-0067>

Timmermans, K., 2023. How supply chain sustainability helps unlock resilience and growth [WWW Document]. Accenture. URL <https://www.accenture.com/za-en/insights/supply-chain-operations/supply-chains-key-unlocking-net-zero-emissions> (accessed 4.27.23).

TOYOTA, 2022. North American Environmental Sustainability Report 2022 [WWW Document]. Toyota North Am. Environ. Sustain. Rep. URL https://www.toyota.com/content/dam/tusa/environmentreport/downloads/2022NAER_Final.pdf

Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A.K., Sharma, S., Singh, J., Pimenov, D.Y., Giasin, K., 2021. An Innovative Agile Model of Smart Lean–Green Approach for Sustainability Enhancement in Industry 4.0. *J. Open Innov. Technol. Mark. Complex.* 7, 215. <https://doi.org/10.3390/joitmc7040215>

Udokporo, C.K., Anosike, A., Lim, M., Nadeem, S.P., Garza-Reyes, J.A., Ogbuka, C.P., 2020. Impact of Lean, Agile and Green (LAG) on business competitiveness: An empirical study of fast moving consumer goods businesses. *Resour. Conserv. Recycl.* 156. <https://doi.org/10.1016/j.resconrec.2020.104714>

UN, 2022. For a livable climate: Net-zero commitments must be backed by credible action [WWW Document]. *Clim. Action*. URL <https://www.un.org/en/climatechange/net-zero-coalition#:~:text=What is net zero%3F,oceans and forests for instance.> (accessed 12.21.23).

UN, 2021. From Mission Zero to Climate Take Back: How Interface is Transforming its Business to Have Zero Negative Impact | Global [WWW Document]. United Nations Clim. Chang. URL <https://unfccc.int/climate-action/momentum-for-change/climate-neutral-now/interface>

UN, 2020. Take Action for the Sustainable Development Goals [WWW Document]. *Sustain. Dev. Goals*. URL <https://www.un.org/sustainabledevelopment/sustainable-development-goals/> (accessed 12.21.23).

UN, 2015. THE 17 GOALS - Sustainable Development Goals [WWW Document]. URL <https://sdgs.un.org/goals> (accessed 4.13.22).

- Unilever, 2021. Unilever Sustainable Living Plan 2010 to 2020 [WWW Document]. URL <https://www.unilever.com/files/92ui5egz/production/16cb778e4d31b81509dc5937001559f1f5c863ab.pdf>
- Vimal, K.E.K., Kumar, A., Sunil, S.M., Suresh, G., Sanjeev, N., Kandasamy, J., 2022. Analysing the challenges in building resilient net zero carbon supply chains using Influential Network Relationship Mapping. *J. Clean. Prod.* 379, 134635. <https://doi.org/10.1016/j.jclepro.2022.134635>
- Virmani, N., Agarwal, S., Raut, R.D., Paul, S.K., Mahmood, H., 2022. Adopting net-zero in emerging economies. *J. Environ. Manage.* 321, 115978. <https://doi.org/10.1016/j.jenvman.2022.115978>
- VOGUE, 2021. Fashion is chasing carbon neutrality. Carbon positive is better [WWW Document]. URL <https://www.voguebusiness.com/sustainability/fashion-is-chasing-carbon-neutrality-carbon-positive-is-better-allbirds-reformation-nicholas-kirkwood>
- Wang, Fang, Harindintwali, J.D., Yuan, Zhizhang, Wang, M., Wang, Faming, Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., Chang, S.X., Zhang, L., Rinklebe, J., Yuan, Zuoqiang, Zhu, Q., Xiang, L., Tsang, D.C.W., Xu, L., Jiang, X., Liu, J., Wei, N., Kästner, M., Zou, Y., Ok, Y.S., Shen, J., Peng, D., Zhang, W., Barceló, D., Zhou, Y., Bai, Z., Li, B., Zhang, B., Wei, K., Cao, H., Tan, Z., Zhao, L., He, X., Zheng, J., Bolan, N., Liu, X., Huang, C., Dietmann, S., Luo, M., Sun, N., Gong, J., Gong, Y., Brahushi, F., Zhang, T., Xiao, C., Li, X., Chen, W., Jiao, N., Lehmann, J., Zhu, Y.-G., Jin, H., Schäffer, A., Tiedje, J.M., Chen, J.M., 2021. Technologies and perspectives for achieving carbon neutrality. *Innov.* 2, 100180. <https://doi.org/10.1016/j.xinn.2021.100180>
- Wang, J., Zhao, C., 2022. Reducing carbon footprint in a resilient supply chain: examining the critical influencing factors of process integration. *Int. J. Prod. Res.* <https://doi.org/10.1080/00207543.2022.2063088>
- WTO, 2021. The carbon content of international trade [WWW Document]. World Trade Organ. URL https://www.wto.org/english/news_e/news21_e/clim_03nov21-4_e.pdf
- Wu, P., Feng, Y., 2012. USING LEAN PRACTICES TO IMPROVE CURRENT CARBON LABELLING SCHEMES FOR CONSTRUCTION MATERIALS— A GENERAL FRAMEWORK. *J. Green Build.* 7, 173–191. <https://doi.org/10.3992/jgb.7.1.173>
- Wu, X., Zhu, J., Wang, X., 2021. A review on carbon reduction analysis during the design and manufacture of solid wood furniture. *BioResources* 16, 6212–6230. <https://doi.org/10.15376/biores.16.3.6212-6230>
- Wuest, T., Weimer, D., Irgens, C., Thoben, K., Wuest, T., Weimer, D., Irgens, C., Thoben, K., 2016. Machine learning in manufacturing: advantages, challenges, and applications. *Prod. Manuf. Res.* 4, 23–45. <https://doi.org/10.1080/21693277.2016.1192517>
- Yadav, S., Samadhiya, A., Kumar, A., Majumdar, A., Garza-Reyes, J.A., Luthra, S., 2023. Achieving the sustainable development goals through net zero emissions: Innovation-driven strategies for transitioning from incremental to radical lean, green and digital technologies. *Resour. Conserv. Recycl.* 197, 107094. <https://doi.org/10.1016/j.resconrec.2023.107094>

- 1 Yunus, R., Yang, J., 2012. Critical sustainability factors in industrialised building systems.
2 Constr. Innov. 12, 447–463. <https://doi.org/10.1108/14714171211272216>
- 3 Zhan, Y., Tan, K.H., Ji, G., Chung, L., Chiu, A.S.F., 2018. Green and lean sustainable
4 development path in China: Guanxi, practices and performance. Resour. Conserv. Recycl.
5 128, 240–249. <https://doi.org/10.1016/j.resconrec.2016.02.006>
- 6
7
8 Zhang, A., Tay, H.L., Alvi, M.F., Wang, J.X., Gong, Y., 2022. Carbon neutrality drivers and
9 implications for firm performance and supply chain management. Bus. Strateg. Environ.
10 <https://doi.org/10.1002/bse.3230>
- 11
12
13 Zhu, Q., Geng, Y., Sarkis, J., Lai, K., 2011. Evaluating green supply chain management among
14 Chinese manufacturers from the ecological modernization perspective. Transp. Res. Part
15 E Logist. Transp. Rev. 47, 808–821. <https://doi.org/10.1016/j.tre.2010.09.013>
- 16
17
18 Zou, C., Xue, H., Xiong, B., Zhang, G., Pan, S., Jia, C., Wang, Y., Ma, F., Sun, Q., Guan, C.,
19 Lin, M., 2021. Connotation, innovation and vision of “carbon neutrality.” Nat. Gas Ind. B
20 8, 523–537. <https://doi.org/10.1016/j.ngib.2021.08.009>
- 21
22
23
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List of Appendix

Appendix 1. Details of Respondents Participated in Conducting Validatory Survey, SODEA, and BN

Particulars	Content	No. of Experts	%
Academic Qualification	Ph.D.	8	6%
	Post-Graduate	94	75%
	Graduate	23	18%
Designation	Vice President	7	6%
	General Manager - Manufacturing	37	30%
	Operations Manager	59	47%
	Junior Level Operations Managers	22	18%
Work Experience	26-30+ Years	21	17%
	21-25 Years	24	19%
	16-20 Years	37	30%
	11-15 Years	25	20%
	05-10 Years	18	14%

Appendix 2. Questionnaire for Validatory Survey

On the Scale of 1 to 5, rate whether the identified CSFs are applicable in the Indian Manufacturing Supply Chains. Where, 1 refers to “Strongly Disagree” while 5 refers to “Strongly Agree”.

Group CSFs	Sub-CSFs	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process					
	Availability of Funds for implementing sustainable practices					
	Collaboration among stakeholders					
	Availability of professional expertise					
	Focus on research and development activities to adopt innovative technological solutions					
Government and Legal Factors (CSF2)	Incentive schemes for organisations					
	Promoting sustainability and CO2 emission reduction initiatives					
	Strategic planning and effective roadmap					
	Law and certification					
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals					
Technical Factors (CSF3)	Maintaining sustainability in waste management					
	Carbon footprint reduction					
	Adoption of eco-innovation for achieving net-zero goals					
	Availability of sustainable supplier					

Appendix 3. Responses of Validatory Survey

Group CSFs	Sub-CSFs	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Mean Score
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process	0	3	22	19	81	4.4
	Availability of Funds for implementing sustainable practices	0	0	7	24	94	4.7
	Collaboration among stakeholders	0	4	9	79	33	4.1
	Availability of professional expertise	0	2	17	84	22	4.0
	Focus on research and development activities to advent innovative technological solutions	4	9	14	61	37	3.9
Government and Legal Factors (CSF2)	Incentive schemes for organisations	0	0	0	21	104	4.8
	Promoting sustainability and CO2 emission reduction initiatives	0	2	4	69	50	4.3
	Strategic planning and effective roadmap	15	9	16	54	31	3.6
	Law and certification	7	16	9	61	32	3.8
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	0	0	9	12	104	4.8
Technical Factors (CSF3)	Maintaining sustainability in waste management	0	0	4	25	96	4.7
	Carbon footprint reduction	0	0	18	88	19	4.0
	Adoption of eco-innovation for achieving net-zero goals	0	0	0	34	91	4.7
	Availability of sustainable supplier	4	5	0	27	89	4.5

Appendix 4. Description of CSFs of Sustainable Innovations for Carbon Neutrality

Critical Success Factor	Description	Reference
Adequate support from top management in the implementation process	Skilful and proficient guidance is provided by individuals in positions of authority within an organization. In the context of reforming traditional practices and beliefs, effective leadership and management play a crucial role in initiating and driving radical changes that aim to improve overall performance by implementing sustainable practices to achieve net-zero emission.	(Asmae et al., 2022; de la Vega et al., 2020; de Sousa Jabbour et al., 2019; Debnath et al., 2023; Mathiyazhagan et al., 2022; Mohib et al., 2023; Netland, 2016; Qureshi et al., 2022; Thanki & Thakkar, 2018; Virmani et al., 2022)
Availability of funds for implementation of sustainable practices	Financial capabilities encompass the organization's investment of capital to develop and implement sustainable manufacturing strategies to achieve net-zero emissions. These capabilities involve allocating funds for activities such as employee training, building internal teams with diverse skills, and engaging external consultants.	(de la Vega et al., 2020; de Sousa Jabbour et al., 2019; Fleith de Medeiros et al., 2022; Qureshi et al., 2022; Thanki & Thakkar, 2018; Virmani et al., 2022)
Collaboration among stakeholders	The active engagement, communication, and coordination among stakeholders to achieve a sustainable manufacturing supply chain.	(de Sousa Jabbour et al., 2019; Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022; Virmani et al., 2022)
Availability of Professional Expertise	The proficiency and expertise of employees play a crucial role in the success of organizational strategies. Employees' active involvement and participation enable the organization to achieve its predetermined business goals. Investing in employee training can enhance their skills and performance, leading to overall organizational improvement.	(Asmae et al., 2022; de la Vega et al., 2020; Debnath et al., 2023; Mathiyazhagan et al., 2022; Mohib et al., 2023; Netland, 2016; Thanki & Thakkar, 2018; Tripathi et al., 2021; Zhan et al., 2018)
Focus on research and development activities to advent innovative technological solutions	It conducts scientific research, experiments, and investigations to discover novel ideas and concepts that can lead to the development of innovative technological solutions for sustainable manufacturing and circular supply chains to achieve net-zero emissions.	(Tripathi et al., 2021; Virmani et al., 2022; Dohale et al., 2023b)

Critical Success Factor	Description	Reference
Incentive schemes for organization	Government support through a range of incentives, financial assistance, and policies aimed at encouraging the implementation of quality and productivity improvement practices and tools to achieve net-zero emissions. This support encompasses various initiatives, including technology transfer and development assistance, subsidies, and taxation policies. These measures are essential conditions that contribute to the advancement of sustainable practices across different sectors.	(de Sousa Jabbour et al., 2019; Debnath et al., 2023; Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022; Qureshi et al., 2022; Thanki & Thakkar, 2018)
Promoting sustainability & CO2 Emission reduction initiatives	The efforts and actions are undertaken to encourage and support practices that contribute to environmental sustainability and reduce carbon dioxide (CO2) emissions. This involves promoting and implementing strategies, policies, and activities to minimise the negative impact of human activities on the environment and mitigate climate change.	(de Sousa Jabbour et al., 2019; Qureshi et al., 2022)
Strategic planning and effective roadmap	The process of developing a comprehensive and well-defined strategy to eliminate or offset greenhouse gas emissions, resulting in a carbon-neutral or net-zero emissions state. It involves setting long-term targets and developing a clear roadmap that outlines the steps, actions, and initiatives necessary to transition towards a sustainable and low-carbon future.	(Asmae et al., 2022; de la Vega et al., 2020; Mohib et al., 2023; Netland, 2016; Qureshi et al., 2022; Tripathi et al., 2021; Virmani et al., 2022; Wu et al., 2021)
Law and Certification	The regulatory frameworks, policies, and certification systems established by governments, industry bodies, and organizations to promote and enforce sustainable practices and emission reduction targets.	(de Sousa Jabbour et al., 2019; Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022)

Critical Success Factor	Description	Reference
Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	Organizations can identify opportunities, implement effective measures, and continuously improve their operations to achieve net-zero emissions. It empowers them to make informed decisions, optimize resource utilization, minimize waste, and contribute to a sustainable and low-carbon future.	(Netland, 2016; Qureshi et al., 2022; Tripathi et al., 2021; Zhan et al., 2018)
Maintaining sustainability in waste management	Implementing practices and strategies that ensure environmentally responsible and sustainable handling, treatment, and disposal of waste materials to achieve net-zero emissions.	(Ambilkar et al., 2022; de la Vega et al., 2020; Debnath et al., 2023; Qureshi et al., 2022; Thanki and Thakkar, 2018; Udokporo et al., 2020; Zhan et al., 2018)
Carbon footprint reduction	The deliberate and systematic efforts to minimize or eliminate greenhouse gas (GHG) emissions associated with human activities, aiming to achieve net-zero emissions. It involves quantifying and mitigating the amount of carbon dioxide (CO2) and other GHG emissions released into the atmosphere from various sources, such as energy consumption, transportation, industrial processes, and waste management.	(Debnath et al., 2023; Virmani et al., 2022; Wu et al., 2021)
Adoption of eco-innovation for achieving Net-zero target	Implementing and utilizing environmentally friendly and innovative practices, energy-saving technologies, and processes to reduce greenhouse gas emissions and achieve a net-zero emission state.	(Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022; Virmani et al., 2022; Wu et al., 2021; Zhan et al., 2018)
Availability of sustainable supplier	The presence of suppliers who prioritize sustainability in their operations, products, and services by reducing processes impacting the environment, promoting sustainable practices, and offering sustainable and low-carbon solutions.	(de la Vega et al., 2020; Debnath et al., 2023; Mathiyazhagan et al., 2022; Mohib et al., 2023; Qureshi et al., 2022; Thanki & Thakkar, 2018; Virmani et al., 2022)

Appendix 5. Questionnaire for SODEA

Vote the CSFs according to their relative importance to achieve carbon neutrality or net-zero achievement in the Indian Manufacturing Supply Chains in the corresponding ranks. Kindly tick the ranking place suitable for the corresponding CSFs based on their importance.

Group CSF	1st Place	2nd Place	3rd Place
Managerial (CSF1)			
Government and Legal (CSF2)			
Technical (CSF3)			

Managerial (CSF1)	1st Place	2nd Place	3rd Place	4th Place	5th Place
Adequate Support from top management in the implementation process (CSF11)					
Availability of Funds for implementing sustainable practices (CSF12)					
Collaboration among stakeholders (CSF13)					
Availability of professional expertise (CSF14)					
Focus on research and development activities to advent innovative technological solutions (CSF15)					

Government and Legal (CSF2)	1st Place	2nd Place	3rd Place	4th Place
Incentive schemes for organisations (CSF21)				
Promoting sustainability and CO2 emission reduction initiatives (CSF22)				
Strategic planning and effective roadmap (CSF23)				
Law and certification (CSF24)				

Technical (CSF3)	1st Place	2nd Place	3rd Place	4th Place	5th Place
Know-how of the sustainable and lean tools and techniques to achieve net-zero goals (CSF31)					
Maintaining sustainability in waste management (CSF32)					
Carbon footprint reduction (CSF33)					
Adoption of eco-innovation for achieving net-zero goals (CSF34)					
Availability of sustainable supplier (CSF35)					

Appendix 6. Questionnaire for Bayesian Network

On a scale of 1 to 6, rate the influence of CSFs of sustainable innovations on the net-zero achievement in the Indian Manufacturing Supply Chains. Where 1 refers to “Extremely Low” while 6 refers to “Extremely High”.

Group CSFs	Sub-CSFs	Extremely Low (1)	Very Low (2)	Low (3)	High (4)	Very High (5)	Extremely High (6)
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process						
	Availability of Funds for implementing sustainable practices						
	Collaboration among stakeholders						
	Availability of professional expertise						
	Focus on research and development activities to adopt innovative technological solutions						
Government and Legal Factors (CSF2)	Incentive schemes for organisations						
	Promoting sustainability and CO2 emission reduction initiatives						
	Strategic planning and effective roadmap						
	Law and certification						
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals						
Technical Factors (CSF3)	Maintaining sustainability in waste management						
	Carbon footprint reduction						
	Adoption of eco-innovation for achieving net-zero goals						
	Availability of sustainable supplier						

Appendix 7. Survey for collecting prior probability data for Bayesian Network (BN)

Group CSFs	Sub-CSFs	Low			High			Total Responses	Low	High
		1	2	3	4	5	6			
		EL	VL	L	H	VH	EH			
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process	1	3	16	24	27	54	125	0.16	0.84
	Availability of Funds for implementing sustainable practices	0	0	26	32	51	16	125	0.208	0.792
	Collaboration among stakeholders	1	0	19	44	51	10	125	0.16	0.84
	Availability of professional expertise	0	0	4	16	91	14	125	0.032	0.968
	Focus on research and development activities to adopt innovative technological solutions	7	11	39	38	19	11	125	0.456	0.544
Government and Legal Factors (CSF2)	Incentive schemes for organisations	0	4	2	13	64	42	125	0.048	0.952
	Promoting sustainability and CO2 emission reduction initiatives	0	2	9	25	28	61	125	0.088	0.912
	Strategic planning and effective roadmap	14	9	21	31	21	29	125	0.352	0.648
	Law and certification	2	8	21	36	41	17	125	0.248	0.752
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	0	0	2	19	24	80	125	0.016	0.984
Technical Factors (CSF3)	Maintaining sustainability in waste management	0	0	1	6	27	91	125	0.008	0.992
	Carbon footprint reduction	0	0	2	2	29	92	125	0.016	0.984
	Adoption of eco-innovation for achieving net-zero goals	0	1	2	29	41	52	125	0.024	0.976
	Availability of sustainable supplier	0	2	26	12	24	61	125	0.224	0.776

Critical Factors to Sustaileanant Innovations for Net-Zero Achievement in the Manufacturing Supply Chains

Vishwas Dohale^a, Priya Ambilkar^a, Sachin Kumar Mangla^{c,d,*}, Balkrishna Eknath Narkhede^b

^aBusiness School, Dublin City University, Dublin 9, Ireland; ^bOperations and Supply Chain Management (O&SCM), Indian Institute of Management, Mumbai, India ^cOperations Management, Jindal Global Business School, O. P. Jindal Global University, Haryana, India; ^d Knowledge Management & Business Decision Making, University of Plymouth, UK
(*Corresponding Author)

Abstract

The importance of reducing carbon emissions to safeguard the environment for generations is widely recognized worldwide. Countries are putting in efforts to lower their carbon footprint, aiming towards achieving carbon neutrality also termed as net zero emissions. This research seeks insights from manufacturing experts on how sustaileanant (sustainable + lean) innovations can support the journey towards net zero in manufacturing supply chains, making them more environmentally friendly. We initially determined the critical success factors (CSFs) of sustaileanant innovations that can help achieve net-zero emissions in manufacturing supply chains and validated through manufacturing experts using a validity survey. Further, employing a robust two-step approach involving strong ordering data envelopment analysis (SODEA) and machine learning (ML) based Bayesian network (BN), we aimed to understand the significant CSFs driving this transition from traditional carbon-heavy manufacturing practices to a net zero objective. Our study involved gathering input from 125 professionals in the manufacturing sector for employing SODEA-BN methodologies. The findings highlight that incentive schemes for organizations, availability of professional expertise, and availability of funds for implementing sustaileanant practices are crucial for organizations to transform and achieve carbon neutrality. In this study, the recommendations provided in line with sustainable development goals (SDGs) will guide practitioners and academicians in understanding the critical sustaileanant factors for a successful net-zero achievement.

Keywords – Sustaileanant Innovations, Net-Zero, Manufacturing Supply Chains, Strong Ordering Data Envelopment Analysis, Machine Learning, Bayesian Network

Critical Factors to Sustainable Innovations for Net-Zero Achievement in the Manufacturing Supply Chains

1 Introduction

In the face of escalating environmental challenges and the urgent need to combat climate change, the concept of achieving net-zero emissions (NZE) has gained substantial traction. The global industrial sector struggles to transform its carbon-oriented business processes into carbon neutral to reduce its carbon footprints. The industrial supply chain and logistic network contribute significantly to carbon emissions (Mishra et al., 2022). The complexity of global supply chains involving multiple entities across different countries and continents, amplifies their carbon footprint (COP26, 2021). Long-distance transportation, reliance on fossil fuels, energy-intensive production processes, and waste generation contribute to supply chain emissions. It was estimated that global emissions driven by international trade through the worldwide logistics network would grow from 25% (Dellink et al., 2017; Janssens et al., 2020) to 30% and will further increase with a factor of 3.9 by 2050 (ITF, 2016; WTO, 2021).

The carbon footprint of supply chains can vary across industries and regions. Sectors such as manufacturing, transportation, and agriculture are known to have significant carbon emissions due to their extensive pollution levels and supply chain networks (Dohale et al., 2023c; Muthu, 2019). It has been observed that organizations globally are self-motivated to roll out different innovative solutions to manage their supply chains to make them carbon neutral. Utilizing the resources efficiently, adopting green technologies, and data-driven innovations trigger net zero emissions (Dohale et al., 2024; Mishra et al., 2022; Nyangchak, 2022).

One component of achieving NZE is the integration of sustainable and circular practices within global supply chains (Dohale et al., 2023c). On the other front, avoiding non-value-added activities for energy savings through lean practices can potentially contribute to ecological sustainability. For instance, using a lean approach, General Electric saved 35 million KWH of energy, equivalent to US\$ 3 million in energy costs saved per year and reduced 25,000 metric tons of CO₂ emission (General Electric, 2021). Similarly, Toyota Motors recycled, reused or used approximately 86% of an end-of-life vehicle's material content for energy recovery. This helped them to reduce GHG emissions at their nine plants by 50% by 2030 (TOYOTA, 2022). These examples illustrate the essence of lean and sustainable practices in the quest to combat climate change and achieve net-zero emissions (Cherrafi et al., 2018; Mathiyazhagan et al.,

2022). The body of knowledge, however, is still limited with the research on developing interpretable net-zero supply chains (Mishra et al., 2022). Thus, organizations face difficulties utilizing and executing lean and sustainable innovations to transform their supply chains to carbon neutral. Against this backdrop, this study aims to explore – 1) the concept of lean and sustainable innovations and its potential application in the context of attaining net-zero emissions; and 2) factors driving the smooth execution of lean and sustainable innovations to deploy carbon-neutral practices in their supply chains. The motivation of this research lays a foundation for the following research questions:

RQ 1. What are the critical success factors that help to deploy lean and sustainable (sustaileanant) innovation for achieving carbon neutrality in supply chains?

RQ 2. How do the identified critical success factors of sustaileanant innovations influence carbon neutrality achievement in manufacturing supply chains?

This research attempts to answer these questions to expand the theoretical and managerial horizons on how lean and sustainable innovations can help achieve net-zero emissions within the Indian manufacturing supply chain and logistics. To this effort, we propose to utilize a two-stage approach comprising strong ordering data envelopment analysis (SODEA) followed by machine learning (ML) based Bayesian network (BN) methods. Initially, we conducted a systematic literature review to understand the crux of lean and sustainable (sustaileanant) innovations for gaining net-zero emissions in the supply chain. Thereafter, we identified the critical success factors (CSFs) that will act as rigid support for organizations to transform their supply chain and logistics to achieve net-zero emissions. Using a validity survey, the identified CSFs are validated for the study. This resulted in the finalization of 14 CSFs falling under 3 major categories. Further, we utilize SODEA to determine the most crucial CSFs by determining their priority weights. We then utilized BN to predict the impact of different CSFs on the level of net-zero emission achieved. Finally, a sensitivity analysis is performed to identify the robustness of the model and determine the most influential CSFs.

The remainder of the paper is structured as follows – Section 2 highlights the comprehensive review of literature on net-zero emissions in the supply chain and the critical success factors of lean and sustainable innovations. Section 3 provides the overall research flow and describes the research methods used for this study. The results are discussed in detail in Section 4. The implications of the research are provided in Section 5. Concluding remarks, research implications, and directions to conduct future research are provided in Section 6.

2 Literature Review

The United Nations Sustainable Development Goal (SDG) has declared the ever-happening climate change driven by excessive anthropogenic carbon emissions as one of the most pressing challenges for humanity (UN, 2015). Carbon neutrality, also known as net-zero emission, is a new milestone for organizations to reach in the present era. It remains unclear whether a state of net-zero emission is possible. If so, how can carbon-dominated production systems and supply chains be transformed toward carbon neutrality? As the industrial sector transitions towards a carbon-neutral practice and works towards achieving net-zero emissions, it is imperative that supply chains play a central role in these efforts. Hence, addressing the carbon footprint of global supply chains is crucial in the pursuit of net-zero emissions. Organizations and governments worldwide are increasingly recognizing the need to adopt sustainable practices, optimize logistics, reduce waste, and transition to cleaner energy sources to mitigate the environmental impact of supply chains (Cao et al., 2023; Ghadge et al., 2020).

2.1 Net-Zero in Manufacturing Supply Chains

The concept of a carbon-neutral supply chain has gained increasing attention in recent years as organizations strive to address the urgent need to mitigate climate change (Mishra et al., 2022). According to the United Nations, net zero is “cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests, for instance” (UN, 2022). Industrial logistic networks contribute extensively to the emissions from various supply chain stages, such as raw material extraction, manufacturing, transportation, and end-of-life disposal. The global supply chain contributes to a significant portion of the world's carbon footprint. While it is challenging to determine an exact percentage, studies indicate that the carbon emissions associated with global supply chains are substantial (Vimal et al., 2022). According to a report by Accenture, global supply chains are responsible for up to 60% of the world's greenhouse gas emissions (Timmermans, 2023). Global institutions are competing with each other to build a more carbon-neutral environment. The University of California announced “Carbon Neutrality” as their most ambitious program (Forgie and Carlson, 2018), and the Paris Government set a goal to transform into a carbon-neutral city by 2050 (Horowitz, 2016). Also, manufacturing organisations adopt programs such as the Science Based Targets initiative and the Carbon Disclosure Project (CDP)¹ to usher towards a net-zero emission economy (de Sousa Jabbour et al., 2019).

¹ <https://www.cdp.net/en/investor/engage-with-companies/cdp-science-based-targets-campaign>

A net-zero emission or carbon neutrality in the manufacturing supply chain aims to minimize or offset the greenhouse gas emissions associated with the entire supply chain network, including the production, transportation, and disposal of goods. The concept of a net-zero or carbon-neutral supply chain involves measuring, reducing, and offsetting carbon emissions throughout the supply chain network (Dohale et al., 2024; Seuring and Müller, 2008; Sindhwani et al., 2022). Numerous studies have examined strategies for reducing carbon emissions in supply chains. These strategies include – 1) Improving energy efficiency within the supply chain to reduce carbon emissions (Bai et al., 2022; Zhu et al., 2011); 2) Shifting towards low-carbon transportation modes, such as electric vehicles or alternative fuels, has been identified as a key strategy for achieving carbon neutrality in supply chains (Hohenstein et al., 2015; Li et al., 2023); 3) Collaborating with suppliers to engage in environmental initiatives, foster knowledge sharing, and develop sustainable practices plays a crucial role in achieving carbon neutrality (Chen et al., 2004; Khan et al., 2022; Naranjo et al., 2023); and 4) adoption of renewable energy sources, such as solar or wind power, within supply chain operations can also contribute to achieving carbon neutrality (Birasnav et al., 2022; Christopher et al., 2023). In adopting and implementing these strategies, collaboration among all stakeholders, including governments, businesses, and consumers, is essential to drive sustainable practices and reduce the carbon footprint of global supply chains (Dohale et al., 2023c; Khan and Ali, 2022; Naranjo et al., 2023). One of the promising approaches to achieving these goals is implementing lean and sustainable innovations that can bring a net-zero economy (Bhattacharya et al., 2019).

2.2 Lean and Sustainable Innovations for Carbon Neutrality

The urgency to address climate change has led to a growing recognition of the need for innovative solutions that can drive the transition to a low-carbon economy. In pursuing carbon neutrality, organizations increasingly turn to lean and sustainable innovation practices to reduce emissions and create more environmentally responsible operations (Bhattacharya et al., 2019; Kumar and Mathiyazhagan, 2020). Lean innovations² rooted in the principles of lean thinking and continuous improvement are acting as a promising approach that has gained traction in recent years for developing and implementing strategies to achieve net-zero emissions (Bag, 2023; Ladhadd and Parrish, 2013; Wu and Feng, 2012). While traditional approaches to innovation focus primarily on technological advancements, lean innovation

² <https://fourprinciples.com/expert-opinion/how-lean-digital-supports-companies-in-achieving-net-zero-supply-chains/>

encompasses a broader perspective. It emphasizes the elimination of waste, the optimization of processes, and the continuous search for efficiency in all aspects of an organization's operations (Farias et al., 2019; Naranjo et al., 2023; Netland, 2016; Rötzer et al., 2016).

On the other hand, when lean innovations are combined with a focus on sustainability, i.e. sustaileanant innovations, they offer a powerful framework to address environmental concerns and achieve carbon neutrality encompassing the advantages of both lean and sustainable practises (Cherrafi et al., 2018; Debnath et al., 2023; Hartini and Ciptomulyono, 2015). Thus, the potential pathways can be constructed through deploying lean, green and digital innovation to rearrange the value chain for decarbonization. Figure 1 demonstrates the benefits of sustaileanant innovations towards achieving net-zero emissions.

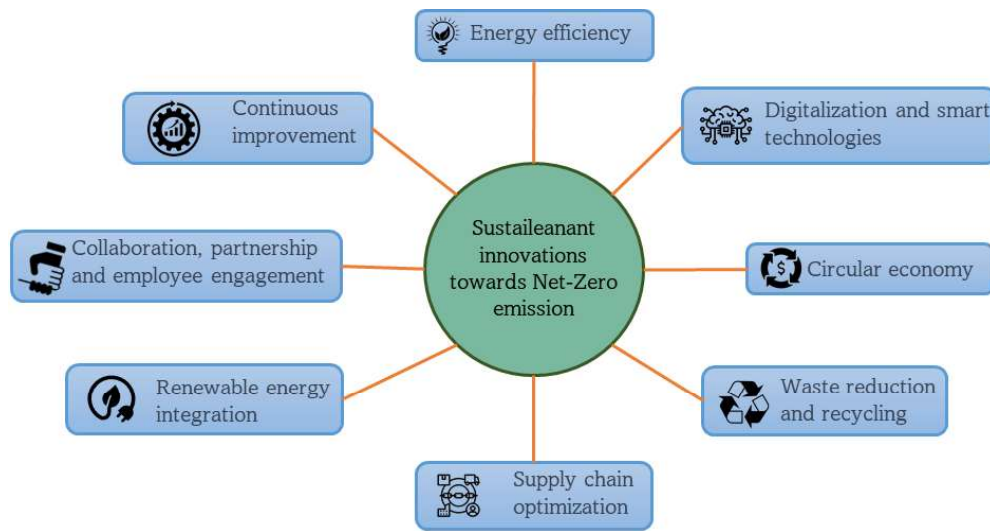


Figure 1. Sustaileanant Innovations for Net-Zero emissions

It has been witnessed that many industries are adopting zero-emission approaches by utilizing sustaileanant innovative solutions to mitigate environmental hazards by reducing greenhouse gas (GHG) emissions. Leading fashion brands, namely – Reformation, Kirkwood, and Allbirds, are becoming carbon-positive and are certified carbon-neutral organizations (VOGUE, 2021). Allbirds, a leading shoe manufacturer, created an innovative product medication by using natural materials like sugarcane-based sweet foam to make carbon-neutral shoes (Allbirds, 2022). The most noticeable and appreciable fact of this innovation is that Allbirds made this innovation accessible to its competitors as well to make the entire industry more sustainable (Hobson and Hagan, 2019). Apart from this, organizations are using sustaileanant thinking and approach in their supply chains to gain a carbon-neutral tag. Some of the notable mentions are as follows –

- Unilever, an international consumer goods company, has embraced lean and sustainable practices to achieve carbon neutrality. The company's Sustainable Living Plan includes ambitious goals, such as sourcing 100% of agricultural raw materials sustainably and becoming carbon-positive in its operations by 2030. Unilever has implemented various initiatives to optimize its supply chain, including reducing transportation distances, improving energy efficiency, and collaborating with suppliers to promote sustainable practices (Unilever, 2021).
- Interface, a global flooring manufacturer, has demonstrated how lean and sustainable innovation can drive carbon neutrality. The company's "Mission Zero" commitment focuses on eliminating negative environmental impacts. By adopting lean principles, such as waste elimination and energy efficiency improvements, the interface significantly reduced energy consumption and carbon emissions (Luqmani et al., 2017; UN, 2021).
- Patagonia, an outdoor clothing and gear company, integrates lean innovation with sustainable practices throughout its supply chain. Patagonia focuses on sourcing recycled and environmentally friendly materials, reducing water and energy consumption in manufacturing, and promoting the repair and reuse of products to extend their lifecycle. By incorporating sustainable principles into its operations, such as efficient inventory management and streamlined distribution processes, Patagonia reduces emissions associated with transportation (Alonso, 2023; Bateman and Bonanni, 2019; Patagonia, 2023).

Although effective in achieving sustainability and reducing carbon footprints, these approaches, i.e. sustainable practices, incur additional costs to organizations and burden the supply chains and overall business strategies (Mahapatra et al., 2021). These costs make organizations resist the strategic implementation of such initiatives. Thus, efforts are needed from organizations to transform their mindset to achieve carbon-neutral operations in the supply chain. Despite that, in their recent review, de Sousa Jabbour et al. (2019) and Mishra et al. (2022) highlighted the urgent need for research on zero-emission or carbon neutrality in the supply chain. The current studies on carbon neutrality consider a macro perspective and undertake carbon neutrality at the global, regional, and national levels by focusing on policy and technological aspects (Chen et al., 2022; Sandberg and Krook-Riekkola, 2022; Zhang et al., 2022). Sandberg and Krook-Riekkola (2022) highlighted the need to conduct quantitative studies in a net-zero industrial context. Some studies have analysed the drivers and barriers of circular economy and carbon neutrality (Dohale et al., 2023b; Kannan et al., 2022; Sindhwani

et al., 2022; Zhang et al., 2022). Although effective in helping implement net-zero initiatives in the supply chain, research on sustainable innovations and their critical success factors for carbon neutrality is nascent. While the strength of these determinants may vary from sector to sector, the Indian manufacturing sector represents a revelatory application case for this study due to its significant carbon footprint. CO₂ emissions from the Indian manufacturing sector in 2014³ were reported as 26.4%. Hence, it shows an extraordinary potential for improvement toward net-zero emissions.

2.3 Research Gaps

Based on the extensive literature review conducted in this study, it is imperative that implementing sustainable innovations in the manufacturing supply chains will have great potential to achieve net-zero goals. However, it is essential to develop a foundationary work that can guide this implementation. We identified several research gaps in the extant literature as follows -

- RG 1.** Most of the literature discusses different lean and sustainable innovations for circular economy and sustainability separately (Orji and Liu, 2020; Qureshi et al., 2022; Schot and Geels, 2008), but fewer efforts are put into identifying the combined role of sustainable innovations in achieving net-zero goals.
- RG 2.** The literature is sparse in determining and consolidating the critical success factors of Sustainable innovations towards net-zero achievement.
- RG 3.** Literature lacks to evaluate and interpret the strength of sustainable innovation to achieve net-zero targets.

3 Research Methodology

3.1 Research Paradigm and Design

Research paradigm, a fundamental step of establishing a philosophical stance (Hegde, 2015; Remenyi et al., 1998), is developed within a scientific discipline as a guiding perspective for a researcher to know what to study, how the study will be carried out, and which suitable methods to utilise (Bryman and Bell, 2015). The research paradigms are categorised as – positivism, realism, interpretivism and pragmatism (Saunders et al., 2009). The present research work is developed within the vicinity of the pragmatism research paradigm, a research stance which focuses on the problem under observation to establish a solution by collecting different

³ <https://knoema.com/atlas/India/topics/Environment/Emissions/CO2-emissions-from-manufacturing-industries-percent>

perspectives to help interpret the data and derive knowledge about the problem (Saunders et al., 2020; Shali, 1986; Yunus and Yang, 2012). The research question is the fundamental determinant of the pragmatic stance (Saunders et al., 2009). As a research paradigm, pragmatism offers legitimacy to use mixed methods of qualitative and quantitative nature in a single study to answer research questions (Yunus and Yang, 2012). Based on the pragmatism paradigm, this study utilises a mixed-method research design, consisting of a systematic literature review, strong ordering data envelopment analysis (SODEA) and Bayesian network (BN) methods to address the RGs and evaluate the CSFs of sustainable innovations to achieve net-zero emission in Indian manufacturing supply chains. Initially, the CSFs for sustainable innovation are identified through a systematic literature review and validated through experts using a validity survey. The detailed research framework to conduct the current study is presented in Figure 2. In the following section, we described the SODEA and BN methods.

3.2 Identification of CSFs of Sustainable Innovation

A systematic literature review (SLR) is carried out to identify the critical success factors (CSFs) of sustainable innovations to achieve net-zero targets within the supply chain of manufacturing organizations. We investigated the pertinent literature thoroughly to identify relevant research articles over the major academic databases, including – Scopus, web of science, and EBSCOhost, iteratively. We searched two keyword clusters – 1) related to sustainable innovations for carbon neutrality, such as – "net-zero", "carbon neutrality", "carbon neutral", "net zero", "climate neutrality", "decarbonization", "lean", "green practices", "sustainable practices", "innovations"; and 2) related to CSFs as "factors", "determinants", "enablers", "critical success factors", "critical factors", etc. in the title/abstract/keywords field.

The keyword clusters are combined using Boolean operators (AND/OR). Keywords from the same clusters are combined using OR operator, while the different cluster keywords are coupled with AND operator. The initial search produced a sample of 576 relevant articles. Further, articles having duplication, not aligning with the scope, erratum, notes, corrigendum, or written in a language other than English are excluded. We only included articles published in peer-reviewed journals from 2016 onwards (i.e. within a span of 5-7 years) to have relevance in the current era. This resulted in the final sample of 32 research articles used for conducting this study and identifying suitable CSFs. These 32 research articles discuss the domain of study in depth and help to build the foundation of this study.

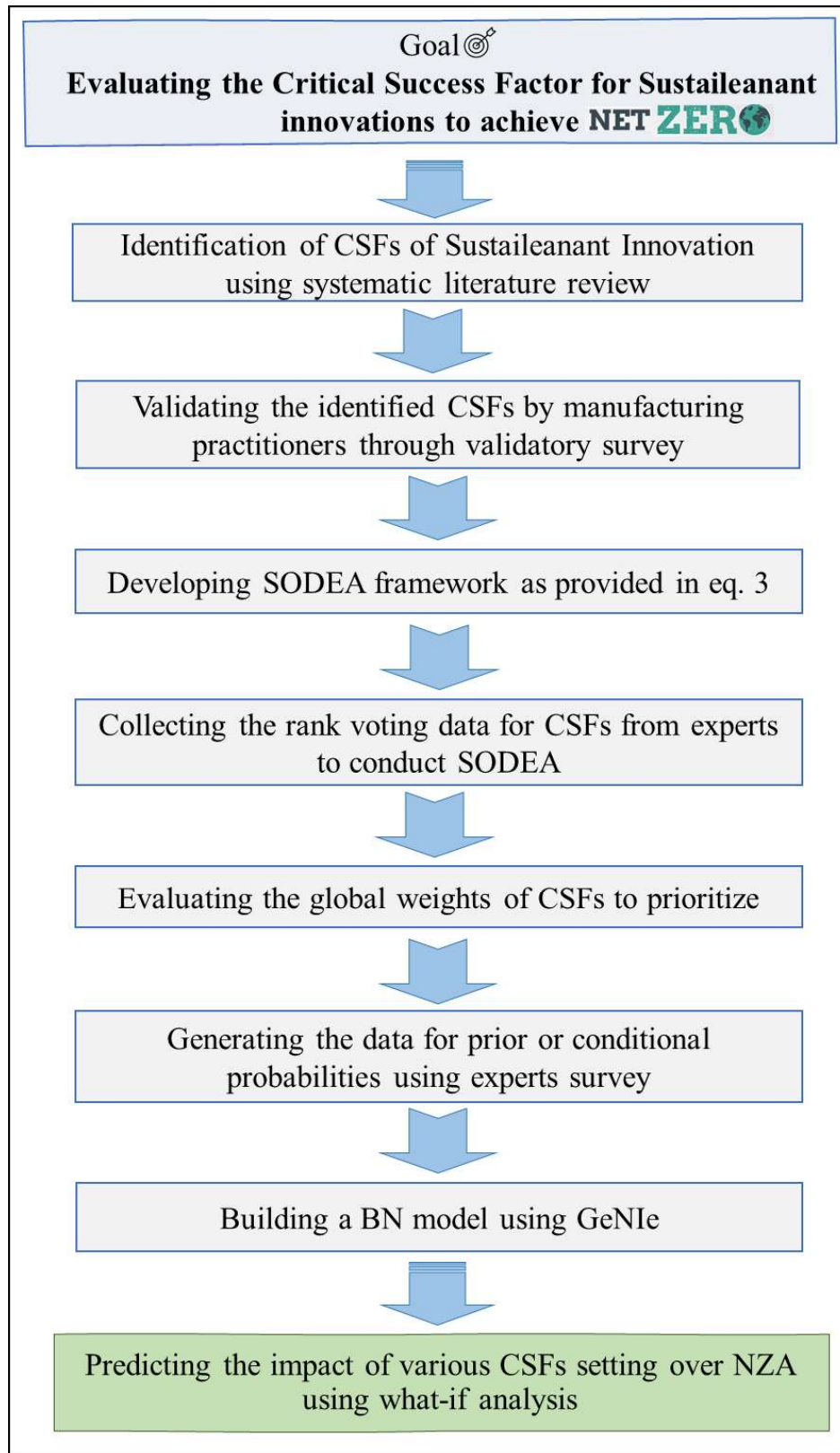


Figure 2. Research Approach

Further, digging down into those 32 articles, we determined that 15 articles have highlighted the list of critical success factors. The detailed procedure to carry-out SLR is illustrated in Figure 3. We analysed the list of CSFs provided in the 15 articles. Reading the definitions of the CSFs and understanding their meanings, we arrived at 14 unique CSFs that cover both lean and sustainability philosophies., which fall under 3 major groups.

We then used a validity survey method to check the relevance and reliability of the 14 identified CSFs for the study's context, i.e., the Indian manufacturing supply chain, using industrial experts' opinions. We initially contacted 196 experts to validate the identified CSFs. Out of these, 125 experts showed interest and participated in the validity survey. Further, all 125 experts responded to the complete questionnaire of the validity survey. This depicts a response rate of 64%. It is reported in the existing literature that a response rate of > 20% is adequate for gaining valuable insights into the problem through surveyed data (Dohale et al., 2024; Majumdar et al., 2021; Malhotra and Grover, 1998). The profile of participants and detailed questionnaire for validity survey are provided in Appendix 1 and 2, respectively. The experts were asked to assign scores to the identified CSFs based on their relevance using the five-point Likert scale (Strongly Disagree = 1; Strongly agree = 5). CSFs obtaining a mean score of ≥ 3.0 are retained for the study (Dohale et al., 2023b; Majumdar et al., 2021). The responses of the validity survey are provided in Appendix 3. All 14 CSFs falling under 3 groups, i.e. managerial, Governmental and legal, and technical factors, are validated by experts. The description of all CSFs is provided in Appendix 4.

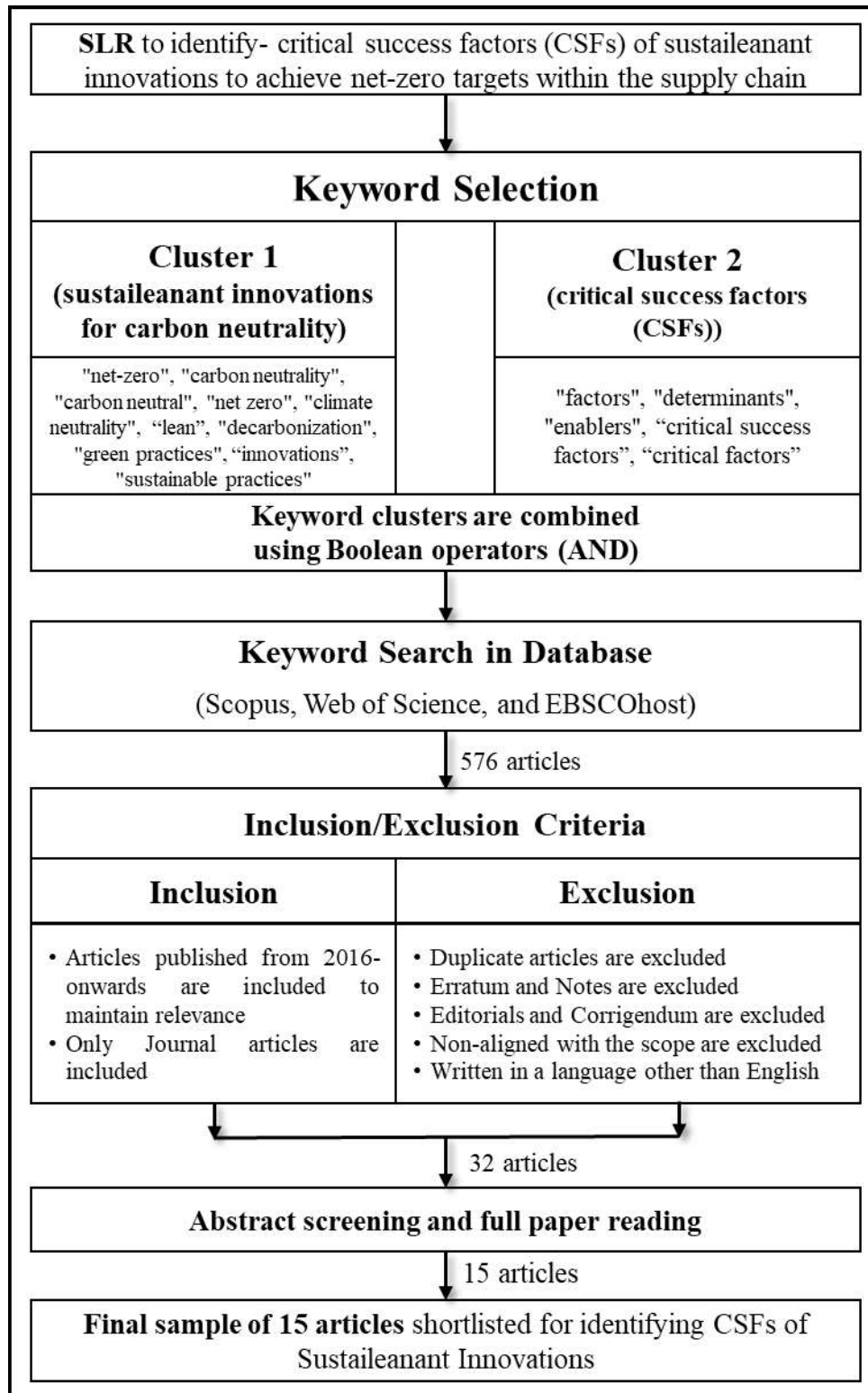


Figure 3. Stepwise procedure for SLR

Table 1. Critical Success Factors of Sustainable Innovations for Net-Zero Achievement

Sr No.	#CSF	Critical Success Factors	References*														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CSF1			Managerial Factors														
1	CSF11	Adequate support from top management in the implementation process	✓	✓		✓	✓			✓		✓	✓	✓	✓	✓	✓
2	CSF12	Availability of funds for implementation of sustainable practices		✓		✓				✓		✓	✓				
3	CSF13	Collaboration among stakeholders				✓						✓					
4	CSF14	Availability of Professional Expertise	✓	✓	✓		✓			✓		✓				✓	✓
5	CSF15	Focus on research and development activities to advent innovative technological solutions						✓						✓			
CSF2			Governmental and Legal Factors														
6	CSF21	Incentive schemes for organization		✓		✓						✓	✓	✓			✓
7	CSF22	Promoting sustainability & CO2 Emission reduction initiatives				✓							✓				
8	CSF23	Strategic planning and effective roadmap	✓					✓		✓				✓	✓		✓
9	CSF24	Law and Certification				✓						✓					
CSF3			Technical Factors														
10	CSF31	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	✓		✓				✓					✓			
11	CSF32	Maintaining sustainability in waste management		✓	✓		✓						✓			✓	
12	CSF33	Carbon footprint reduction														✓	✓
13	CSF34	Adoption of eco-innovation for achieving Net-zero target			✓			✓		✓		✓			✓		
14	CSF35	Availability of sustainable supplier		✓			✓			✓		✓	✓	✓	✓	✓	✓

***References:** 1 - (Netland, 2016), 2 - (Thanki and Thakkar, 2018) 3 - (Zhan et al., 2018), 4 - (de Sousa Jabbour et al., 2019), 5 - (de la Vega et al., 2020), 6 - (Kumar et al., 2020), 7 - (Tripathi et al., 2021), 8 - (Wu et al., 2021), 9 - (Asmae et al., 2022), 10 - (Fleith de Medeiros et al., 2022), 11 - (Mathiyazhagan et al., 2022), 12 - (Qureshi et al., 2022), 13 - (Virmani et al., 2022), 14 - (Debnath et al., 2023), 15 - (Mohib et al., 2023)

3.3 Strong Ordering Data Envelopment Analysis

SO-DEA is one of the most popular methods to rank the attributes by computing the weighted sum of the votes received by each attribute and determining their priority weights. SO-DEA, also known as the voting analytical hierarchy process (VAHP), is used to solve multi-criteria decision-making problems (Hadi-Vencheh and Niazi-Motlagh, 2011; Liu and Hai, 2005). Liu and Hai (2005) first utilized SO-DEA based VAHP, a modified version of AHP, to evaluate the suitable supplier (Pishchulov et al., 2019; Sipahi and Timor, 2010). The roots of SO-DEA were found in the 1990s. In the seminal work, Cook and Kress proposed a DEA-based procedure which helps rank the candidates in a preferential election (Cook and Kress, 1990). Each of the voters, based on their preferences, ranks the candidates at different places as - 1st, 2nd, 3rd, ..., Sth place.

Further, Green, Doyle, and Cook (1996) modified this model, referred to as ‘‘Green’s method’’ in which authors set constraints to weights. Green’s method comprises two sub-methods to set constraints: (1) the difference of weights between consecutive places, i.e., Sth place and (S+1)th place, is allowed to be zero; (2) The difference of weights between consecutive places must be strictly more than zero. Assume that there are R criteria for ranking. Let there be n voters (respondents). Each voter assigns the weight u_{rs} to maximize the weighted sum of the votes to r^{th} criteria at s^{th} place, where the weighted sum is represented by θ_{rr} . The first set of constraints proposed by Green et al. (1996) is termed as ‘‘Green’s Weak Ordering’’ method, which is represented as –

$$\begin{aligned}
 \theta_{rr} &= \max \sum_{s=1}^S u_{rs} x_{rs} \\
 \text{Subjected to, } \quad \theta_{rp} &= \sum_{s=1}^S u_{rs} x_{rp} \leq 1 \quad (p = 1, 2, \dots, R) \\
 u_{r1} - u_{r2} &\geq u_{r2} - u_{r3} \geq \dots \geq u_{rS-1} - Su_{rS} \geq d(S-1, \varepsilon) \geq 0 \\
 u_{r1} &\geq u_{r2} \geq u_{r3} \geq \dots \geq u_{rS} \geq 0
 \end{aligned} \tag{1}$$

Where, $d(S-1, \varepsilon)$ in equation (1) is the discriminating intensity function that denotes the gap between S^{th} versus $(S+1)^{\text{th}}$, and ε denotes the discriminating factor. The second method by Green et al. (1996), in which weights between consecutive places are kept more than zero, is known as ‘‘Green’s Strong Ordering Method’’ and represented as –

$$\begin{aligned}
& \theta_{rr} = \max \sum_{s=1}^S u_{rs} x_{rs} \\
& \text{Subjected to, } \theta_{rp} = \sum_{s=1}^S u_{rs} x_{rp} \leq 1 \quad (p = 1, 2, \dots, R) \\
& u_{r1} - u_{r2} \geq u_{r2} - u_{r3} \geq \dots \geq u_{rS} - Su_{rS} \geq d(S, \varepsilon) = \varepsilon \geq 0 \\
& u_{r1} \geq u_{r2} \geq u_{r3} \geq \dots \geq u_{rS} \geq \varepsilon
\end{aligned} \tag{2}$$

Here, x_{rs} denotes the total number of votes received to the r^{th} criterion given by n voters for s^{th} place. Some numbers will be obtained for x_{r1} as first place, x_{r2} as second place, and x_{rS} for S^{th} place, $r = 1, 2, \dots, R$; $s = 1, 2, \dots, S$; and $d(S, \varepsilon) = \varepsilon$ appearing in the aforementioned equation (2) signifies the difference in weights between S^{th} and $(S+1)^{\text{th}}$ place. However, Green's method comprises certain shortcomings as – (a) application to concrete examples and (b) total ranking changes with change in ε value.

Later, Noguchi et al. (2002) developed a strong ordering method to tackle the shortcomings of Green's method. Moreover, Noguchi's strong ordering method effectively evaluates single and multi-purpose problems (Hadi-Vencheh and Niazi-Motlagh, 2011; Hai and Liu, 2007). In the total ranking method using DEA, ‘‘Noguchi's strong ordering’’ is given as:

$$\begin{aligned}
& \theta_{rr} = \max \sum_{s=1}^S u_{rs} x_{rs} \\
& \text{Subjected to, } \theta_{rp} = \sum_{s=1}^S u_{rs} x_{rp} \leq 1 \quad (p = 1, 2, \dots, R) \\
& u_{r1} \geq 2u_{r2} \geq 3u_{r3} \geq \dots \geq Su_{rS} \\
& u_{rS} \geq \varepsilon \\
& \varepsilon \geq \frac{2}{n \times S(S+1)}
\end{aligned} \tag{3}$$

Noguchi's strong ordering method is the basis for calculating the weights of attributes using the SO-DEA method (Ayyildiz and Taskin Gumus, 2021; Dohale et al., 2023a; Liu and Hai, 2005). The weights are evaluated from rank voting data along with the SO-DEA method (Azadeh et al., 2009; Soltanifar and Hosseinzadeh Lotfi, 2011). In this work, we propose to utilize the SO-DEA model for evaluating the priority weights of CSFs.

The rationale for using SO-DEA over other popular multi-criteria decision-making (MCDM) methods is due to its benefits, as given below:

- SO-DEA uses a linear programming formulation, making it mathematically sound, unlike many MCDM methods (Soltanifar and Hosseinzadeh Lotfi, 2011).
- SO-DEA is easy to understand and provides equal opportunity to all the experts for voting and assessing the reasonableness of ranking (Azadeh et al., 2009; Dohale et al., 2021).
- SO-DEA has no restriction over the number of experts, unlike other MCDM methods. In SO-DEA, experts can vary from 8 to more than 100 (Ayyildiz and Taskin Gumus, 2021; Dohale et al., 2021).
- SO-DEA has no restriction over the number of attributes. Typically, in many MCDM methods, there are limitations for the criteria under evaluation, such as 9 criteria in the best-worst method or AHP/ANP (Rezaei, 2015; Saaty, 2008).

Since the purpose of the research is to uncover novel insights and the influence of CSFs of sustainable innovations for NZA in an exploratory manner, it is desirable to have inputs from multiple experts. As SODEA outperforms well compared to any other MCDM in capturing the data from multiple experts and analyzing it mathematically, it has been selected as most appropriate for the present study.

Deployment of the appropriate voters or respondents with adequate expertise plays a vital role as the results rely on the experts' know-how. Hence, we utilized four critical expert selection criteria to retain suitable respondents/voters – i) Since the research is related to the manufacturing industry, experts shall be from a manufacturing background; ii) knowledge about carbon neutrality and its associated activities; iii) Experience of at least five years in the area of net-zero or carbon emission reduction, green, lean, and sustainable practices in the manufacturing industry; and iv) Enthusiasm to participate in the study (Bokrantz et al., 2017; Dohale et al., 2021).

Initially, we contacted 207 manufacturing experts. Further, we checked whether a particular expert is equipped with at least five years in the area of net-zero or carbon emission reduction, green, lean, and sustainable practices (as mentioned in criteria 2) to ensure the suitability of a particular respondent for the study. Thus, based on all four criteria, 125 respondents out of 207 from Indian manufacturing industries were shortlisted for conducting the SODEA procedure. These 125 experts are the same as validity surveys, making the responses consistent. The

ranking data is collected from the 125 shortlisted voters for all the CSFs (respondents). The questionnaire for collecting ranking data for SODEA is provided in Appendix 5. Whereas the ranking data is shown in Table 2. The SODEA model shown in equation 3 is used to compute the priority weights using the ranking data.

Table 2. Rank Voting Data for CSFs of sustaileanant practices

Group CSF	1st Place	2nd Place	3rd Place
CSF1	71	26	28
CSF2	78	16	31
CSF3	81	31	13

Managerial	1st Place	2nd Place	3rd Place	4th Place	5th Place
CSF11	24	36	34	31	0
CSF12	26	39	29	24	7
CSF13	24	34	16	29	22
CSF14	32	31	29	19	14
CSF15	21	13	24	22	45

G and L	1st Place	2nd Place	3rd Place	4th Place
CSF21	118	5	2	0
CSF22	101	21	3	0
CSF23	94	16	7	8
CSF24	99	19	4	3

Technical	1st Place	2nd Place	3rd Place	4th Place	5th Place
CSF31	78	34	13	0	0
CSF32	76	29	20	0	0
CSF33	86	34	5	0	0
CSF34	81	29	15	0	0
CSF35	69	28	22	6	0

3.4 Bayesian Network

BN is one of the most powerful predictive ML-based statistical operation tools used for complex decision-making (Hosseini et al., 2020). Researchers have predominantly used BN for solving intricate problems consisting of uncertainty (Hosseini et al., 2020; Hosseini and Barker, 2016a; Kaya et al., 2023). BN follows Bayes's theorem and is based on statistical learning theory (Castillo et al., 1997). BN graphically shows the probabilistic interlinks

between the attributes (Wuest et al., 2016). In BN, the directed acyclic graphs (DAG) are used to model the probabilistic interdependencies between the two attributes, viz. variables, factors, risks, etc. DAG consists of various nodes connected through arcs. The attributes are represented through nodes, while the probabilistic dependencies between attributes are shown using the arcs (Hosseini et al., 2020; Hosseini and Ivanov, 2021). A Conditioned Probability Table (CPT) or Node Probability Table (NPT) is assigned to every node to define the conditional probabilities of the attribute.

BN possesses certain additive benefits over other ML techniques, such as – i) BN evaluates attributes with a qualitative and quantitative nature; ii) Even with limited data, BN effectively solves the problem under study; iii) It provides an ability of rigorous learning; and 4) The outputs of BN are easily understood and interpretable (Dohale et al., 2022a; Hosseini and Sarder, 2019). BN can capture the strength of interrelationships more efficiently than the other graphical approaches, namely, social network analysis, DEMATEL, and interpretive structural modelling (ISM) (Kamble et al., 2021). Furthermore, BN can effectively conduct what-if analysis to understand the impact of change in the probability of parent or input node attributes over the output or target node (Dohale et al., 2024; Hosseini and Barker, 2016a). As the study focuses on determining the influence of each CSF of sustainable innovation on NZA, it is required to have a predictive analytical model. Since qualitative data through a survey needs to be collected from experts, and BN handles such data effectively, it has been considered to be a suitable method for the present research work.

In this study, we evaluated and predicted the impact of CSFs of sustainable innovations on the achievement of carbon neutrality and determined the most influential CSFs. In this study, the target or output node is set as the net-zero achievement, while the 14 CSFs are the input nodes, and the 3 group CSFs are the intermediate nodes. In BN, the prior probabilities of input nodes are used as data to develop a problem. The data for prior probabilities of nodes can be retained through system-generated real data or expert surveys (Dohale et al., 2022a; Wuest et al., 2016).

We utilized a method proposed by Dohale et al. (2022) for collecting the prior probability data. In this research, the data for the prior probabilities of the input nodes, i.e., 14 CSFs, is collected through a survey using the shortlisted 125 respondents deployed for a validity survey and SODEA. Having similar experts in all methods helps to achieve homogeneity in opinions. The survey comprises questions related to the influence of CSFs on the achievement of net-zero emissions in supply chains. For example, experts are asked the question– "According to you,

what level of influence does 'Professional Expertise (CSF14)' have in the net-zero achievement in manufacturing supply chains?" The experts provided their responses over a six-point Likert scale (1 – Extremely Low (EL); 2 – Very Low (VL); 3 – Low (L); 4 – High (H); 5 – Very High (VH); 6 – Extremely High (EH). The experts' responses were classified into two categories – Low (L, VL, and EL) and High (H, VH, and EH). The survey questionnaire and its responses for generating prior probabilistic data of BN are provided in Appendix 6 and 7.

Based on the experts' responses, the probabilities of the influence of CSFs were determined into the Low and High categories. For example, the responses received for 'professional expertise (CSF14)' CSF are – 14 (EH), 91 (VH), 16 (H), 4 (L), and 0 for both (VL) and (EL). This implies that 121 (14+91+16) out of 125 experts prefer high values while the remaining 4 prefer low values. Thus, the probabilities of high and low values are computed as: $\left(\frac{121}{125}\right) = 0.968$ and $\left(\frac{4}{125}\right) = 0.032$, respectively. Similarly, the prior probabilities of all the other CSFs are computed in high and low categories. The prior probabilities are used to develop a BN model. In this study, we deployed the GeNIe package, one of the most utilized software for building the BN model. Ease of working in the GeNIe platform, handling complex problems with a large volume of data, and the ability to generate precise results are the forte and noteworthy advantages of GeNIe. The BN model developed in GeNIe is shown in Figure 4.

4 Results and Discussions

The results obtained through SODEA and Bayesian network methods are discussed in detail in this section.

4.1 Results from SODEA

The SODEA model shown in equation 3 is used to compute the relative weights of CSFs of sustaileanant innovations for achieving carbon neutrality using weights using the ranking data provided in Table 2. The weight calculations ae presented in Table 3. The CSFs are then prioritized according to their global weights, as highlighted in Table 3. The results achieved through SODEA uncover some critical and interesting findings. In the group factors, almost every CSF has received the same weight with a marginal difference. Technical (CSF3) and Govt. and Legal (CSF 2) factors have gained more weight than managerial (C1). Technical know-how is crucial in implementing strategic decisions and practices (Dohale et al., 2023b; Zou et al., 2021). Whereas managerial factors are critical in implementing and brainstorming unique ideas for net-zero achievement.

One of the prime KPIs of managers in manufacturing industries has been achieving the desired sustainability targets and carbon-neutral goals (Dohale et al., 2022c; Sindhvani et al., 2022). However, in most cases, organizations possess the required understanding but lack appropriate management strategies for driving decarbonization through their operations and supply chains. Hence, managers must be equipped with adequate professional expertise about the skills required to monitor the implementation of sustainable practices to achieve net-zero targets (de Sousa Jabbour et al., 2019; Netland, 2016; Virmani et al., 2022). The results achieved through SODEA also validated this statement as, in terms of sub-CSFs within managerial factors (CSF1), availability of professional expertise (CSF14) ranked 1 with a global weight of 0.0693. Apart from this, the availability of the sufficient amount of funds required for investing in sustainable innovations to achieve net zero emission strategies are crucial. Until adequate funds are available, implementing decarbonization initiatives will be on a toss. Manufacturing practitioners can seek help from the Government as a funding body to obtain subsidies for moving toward these initiatives.

Table 3. Weight Calculation of Sustainable CSFs

Group CSFs	Relative weight of group CSFs	Normalized weight of group CSFs (Wg)	Sub CSFs	Relative weights of Sub-CSFs	Normalized weight of sub-CSFs (Ws)	Global Weights (Wg × Ws)
CSF1	0.9256	0.3208	CSF11	0.9792	0.2114	0.0678
			CSF12	0.9842	0.2125	0.0682
			CSF13	0.8960	0.1934	0.0620
			CSF14	1.0000	0.2159	0.0693
			CSF15	0.7726	0.1668	0.0535
CSF2	0.9599	0.3327	CSF21	1.0000	0.2689	0.0895
			CSF22	0.9285	0.2497	0.0831
			CSF23	0.8776	0.2360	0.0785
			CSF24	0.9127	0.2454	0.0816
CSF3	1.0000	0.3466	CSF31	0.9490	0.2013	0.0698
			CSF32	0.9283	0.1969	0.0682
			CSF33	1.0000	0.2121	0.0735
			CSF34	0.9602	0.2036	0.0706
			CSF35	0.8774	0.1861	0.0645

Manufacturers have a restricted view about implementing sustainable innovations in their operations and supply chains for net-zero achievement due to the additional cost incurred in it

(Sindhwani et al., 2022). Thus, the incentivization from the Governmental can encourage manufacturing professionals to adopt sustainable innovations for bringing carbon-neutral supply chains. Apart from this, an awareness campaign about the sustainability and CO₂ reduction initiatives to achieve net-zero emissions and their benefits to the industry through its implementation can help practitioners gain more profound knowledge (Dohale et al., 2023c; Sindhwani et al., 2022). The role of the Government in taking legal provisions and communicating and imposing different sustainability initiatives is crucial in achieving these carbon-neutral goals (Muthu, 2019; Sindhwani et al., 2022). Legal certifications are crucial drivers and facilitators of green supply chain initiatives (Dohale et al., 2023c; Govindan et al., 2016). It has been observed that once policies are converted into mandatory laws, manufacturers feel pushed to substantially transform their activities in line with net-zero targets (Govindan et al., 2016; Majumdar and Sinha, 2019; Sindhwani et al., 2022).

Lean, Green and sustainable practices (LGSPs) involve innovative environment-friendly techniques within the operations and supply chain (Bhattacharya et al., 2019), which can help achieve a sector's overall sustainable development goals (Nyangchak, 2022; Oelze, 2017; Wang and Zhao, 2022). However, adequate knowledge of the available sustainable and lean tools and techniques to achieve net-zero goals is a fundamental requirement. Adopting eco-innovative sustainable mechanisms is another way of achieving carbon neutrality (Fleith de Medeiros et al., 2022; Virmani et al., 2022). Global manufacturing organizations are seeking new technological interventions, particularly Industry 5.0. Industry 5.0 is conceived as more sustainable and resilient⁴, where interactive human-machine platforms can develop (Ghobakhloo et al., 2022). Since industry 5.0 is more man-machine-centric, it can help resolve the issue of fear of unemployment. Industries worldwide are collaborating to develop sustainable ways to overcome the issues of carbon dominance in the manufacturing industry. Organizations to reduce their carbon footprints passionately work on developing methods that help scrap carbon dioxide off. Carbon offsetting is one such eco-innovative that deals with *"processes of compensating for carbon dioxide emissions arising from industrial or other human activity by participating in schemes designed to make equivalent reductions of carbon dioxide in the atmosphere"* (Rayer et al., 2022).

⁴https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/industry-50-towards-more-sustainable-resilient-and-human-centric-industry-2021-01-07_en

4.2 Bayesian Network and Sensitivity analysis

We utilized BN to determine the influence of each of the CSFs of sustainable innovations on the overall achievement of net-zero goals with the supply chain of the manufacturing industry. We conducted a what-if analysis in GeNIe to compute the impact of the different CSF settings on the NZA. Figure 4 shows a BN model for one of the possible combinations of CSFs and the achieved probabilistic NZA – High = 0.86 and Low = 0.14. We computed the NZA with the various settings of CSFs and enlisted in Table 4. To get a more explicit understanding of the influential CSFs, we conducted a “strength of influence” analysis of CSFs using GeNIe. The result of the analysis is shown in Figure 5. The strength of influence diagram of CSFs shown in Figure 5 depicts incentive schemes for organizations (CSF21), availability of professional expertise (CSF14), availability of funds for implementing sustainable practices (CSF12), maintaining sustainability in waste management (CSF32), carbon footprint reduction (CSF33), and know-how of sustainable tools and techniques (CSF31), are the most influential and shows a significant impact on NZA in the manufacturing industry. The finding of the influence diagram supports the results obtained from SODEA.

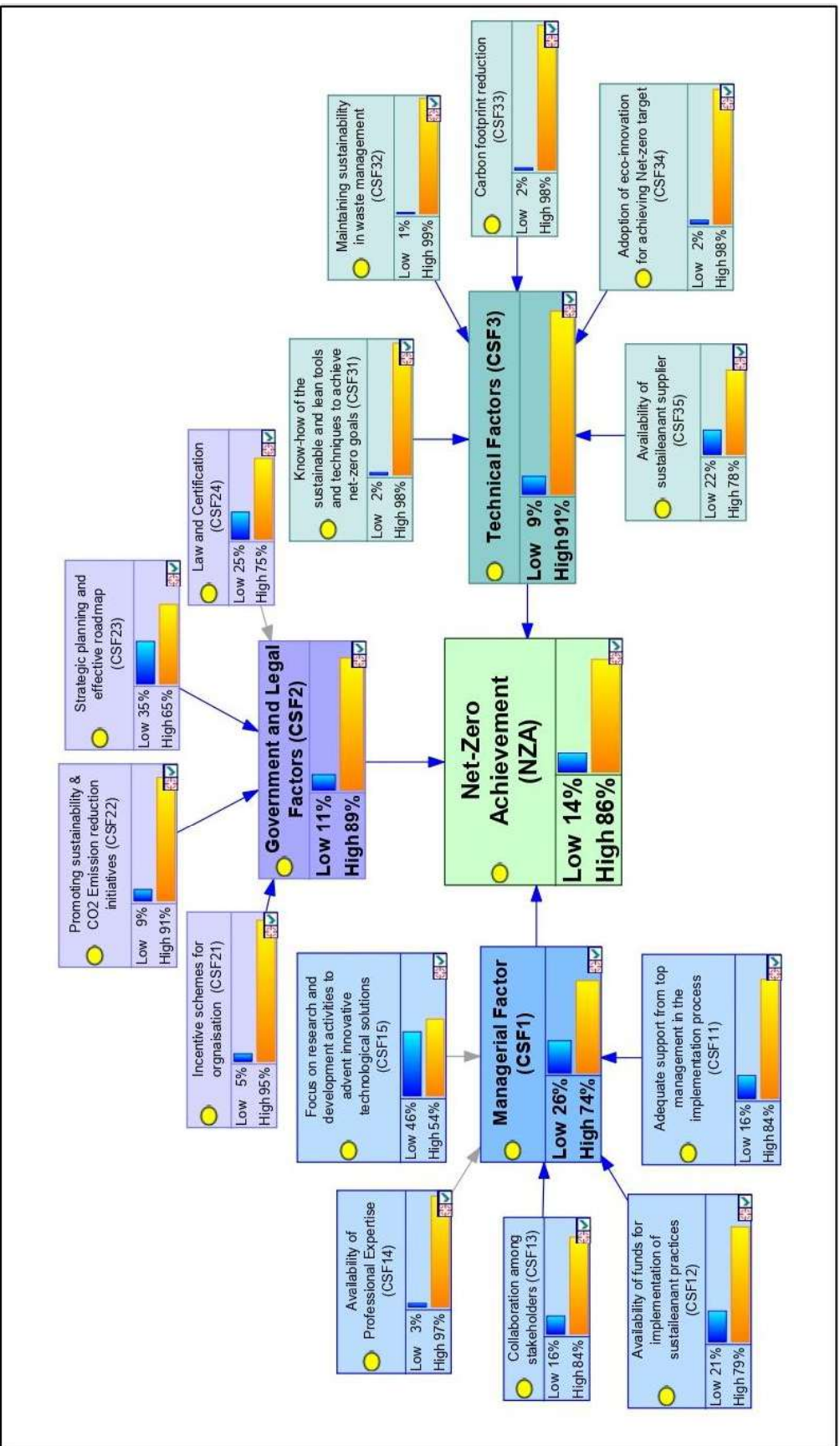


Figure 4. Bayesian Network for the NAZ analysis

Table 4. Impact of conditional probabilities of CSFs over NZA

Managerial (CSF1)					CSF1		Govt. and Legal (CSF2)					CSF2		Technical (CSF3)					CSF3		Net-Zero Achievement (NZA)				NZA		
CSF11	CSF12	CSF13	CSF14	CSF15	L	H	CSF21	CSF22	CSF23	CSF24	L	H	CSF31	CSF32	CSF33	CSF34	CSF35	L	H	CSF1	CSF2	CSF3	L	H	L	H	
L	L	L	L	L	0.999	0.001	L	L	L	L	0.990	0.010	L	L	L	L	L	L	1.000	0.000	L	L	L	1.000	0.000	1.000	0.000
L	L	L	L	L	0.980	0.020	L	L	L	H	0.900	0.100	L	L	L	L	H	L	0.900	0.100	L	L	L	0.930	0.070	0.930	0.070
L	L	L	L	L	0.950	0.050	L	L	L	L	0.850	0.150	L	L	L	L	L	L	0.950	0.050	L	L	L	0.750	0.250	0.750	0.250
L	L	L	L	L	0.945	0.055	L	L	L	H	0.850	0.150	L	L	L	L	H	H	0.950	0.050	L	L	L	0.350	0.650	0.350	0.650
L	L	L	L	L	0.935	0.065	L	L	L	L	0.950	0.050	L	L	L	L	L	L	0.930	0.070	H	L	L	0.750	0.250	0.750	0.250
L	L	L	L	L	0.600	0.400	L	L	L	H	0.950	0.050	L	L	L	L	L	L	0.600	0.400	H	L	L	0.205	0.795	0.205	0.795
L	L	L	L	L	0.800	0.200	L	L	L	L	0.800	0.200	L	L	L	L	L	L	0.800	0.200	H	L	L	0.000	1.000	0.000	1.000
L	L	L	L	L	0.570	0.430	L	L	L	H	0.800	0.200	L	L	L	L	L	L	0.570	0.430	H	L	L	0.000	1.000	0.000	1.000
L	L	L	L	L	0.920	0.080	H	L	L	L	0.550	0.450	L	L	L	L	L	L	0.920	0.080							
L	L	L	L	L	0.725	0.275	H	L	L	L	0.550	0.450	L	L	L	L	L	L	0.730	0.270							
L	L	L	L	L	0.650	0.350	H	L	L	L	0.050	0.950	L	L	L	L	L	L	0.650	0.350							
L	L	L	L	L	0.695	0.305	H	L	L	H	0.050	0.950	L	L	L	L	L	L	0.700	0.300							
L	L	L	L	L	0.650	0.350	H	L	L	L	0.150	0.850	L	L	L	L	L	L	0.650	0.350							
L	L	L	L	L	0.175	0.825	H	L	L	L	0.150	0.850	L	L	L	L	L	L	0.170	0.830							
L	L	L	L	L	0.550	0.450	H	L	L	L	1.000	0.000	L	L	L	L	L	L	0.550	0.450							
L	L	L	L	L	0.150	0.850	H	L	L	L	1.000	0.000	L	L	L	L	L	L	0.150	0.850							
H	L	L	L	L	0.800	0.200				L	0.800	0.200	H	L	L	L	L	L	0.800	0.200							
H	L	L	L	L	0.750	0.250					L	0.750	H	L	L	L	L	L	0.750	0.250							
H	L	L	L	L	0.825	0.175					L	0.825	L	L	L	L	L	L	0.820	0.180							
H	L	L	L	L	0.715	0.285					L	0.715	L	L	L	L	L	L	0.720	0.280							
H	L	L	L	L	0.700	0.300					L	0.700	L	L	L	L	L	L	0.700	0.300							
H	L	L	L	L	0.350	0.650					L	0.350	L	L	L	L	L	L	0.350	0.650							
H	L	L	L	L	0.625	0.375					L	0.625	L	L	L	L	L	L	0.630	0.370							
H	L	L	L	L	0.075	0.925					L	0.075	L	L	L	L	L	L	0.070	0.930							
H	L	L	L	L	0.550	0.450					L	0.550	L	L	L	L	L	L	0.550	0.450							
H	L	L	L	L	0.515	0.485					L	0.515	L	L	L	L	L	L	0.520	0.480							
H	L	L	L	L	0.550	0.450					L	0.550	L	L	L	L	L	L	0.550	0.450							
H	L	L	L	L	0.275	0.725					L	0.275	L	L	L	L	L	L	0.270	0.730							
H	L	L	L	L	0.345	0.655					L	0.345	L	L	L	L	L	L	0.340	0.660							
H	L	L	L	L	0.195	0.805					L	0.195	L	L	L	L	L	L	0.200	0.800							
H	L	L	L	L	0.325	0.675					L	0.325	L	L	L	L	L	L	0.320	0.680							
H	L	L	L	L	0.999	0.001					L	0.999	L	L	L	L	L	L	1.000	0.000							

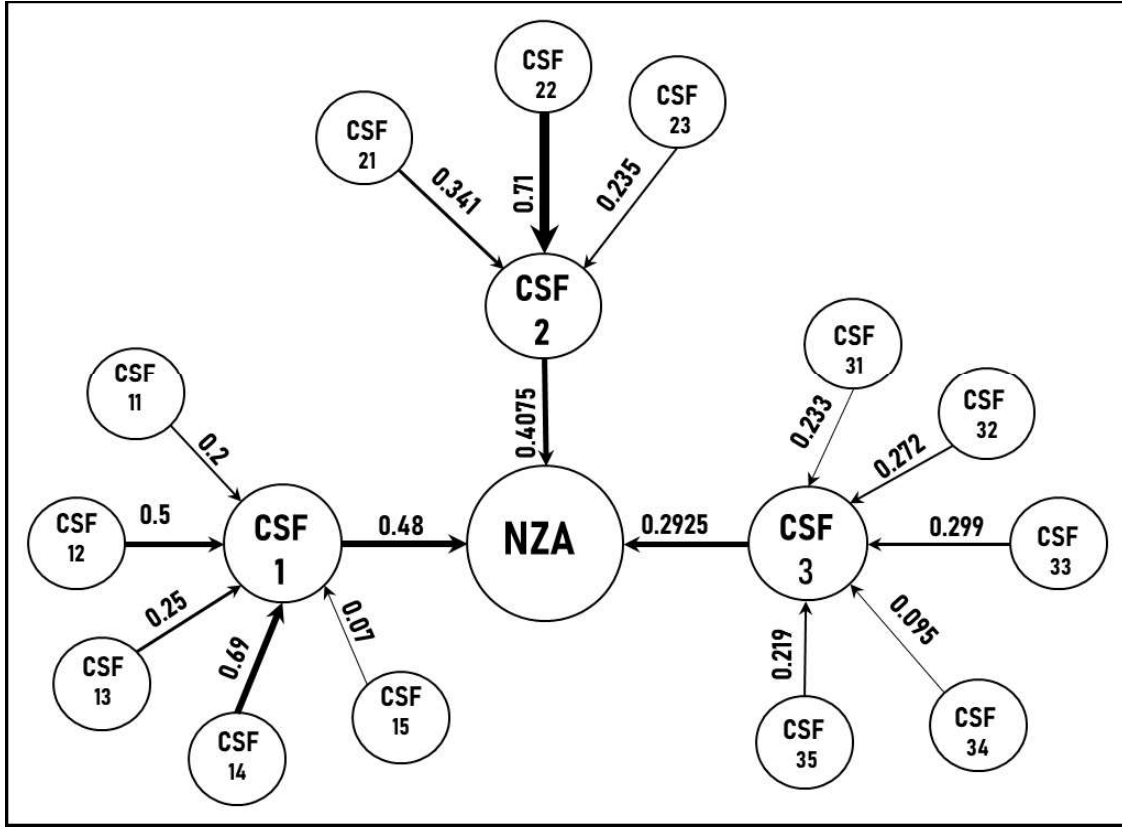


Figure 5. Strength Influence Diagram

Furthermore, to validate the robustness of the model and the results obtained through the proposed BN, we conducted a sensitivity analysis. Sensitivity analysis is the most suitable and practical approach that helps validate expert-built BN models (Dohale et al., 2021; Hosseini and Sarder, 2019). In sensitivity analysis, the assessment of the variation that occurred in the model's outcome with the changes in input parameters is captured (Hosseini and Barker, 2016a). The influential attributes within the model can be easily identified and analysed using sensitivity analysis. Sensitivity analysis also validates whether the model can be replicated in future research or not (Dohale et al., 2022a; Hosseini and Barker, 2016b).

GeNIe has an in-built feature to conduct the sensitivity analysis and offers the results in a Tornado graph (GeNIe, 2022). This study quantifies the impact of 14 CSFs under 3 group CSFs on the achievement of net-zero emission in Indian manufacturing supply chains. Thus, in this model, the 14 CSFs are the sensitive nodes to check their influence over the target node, i.e., NZA. The sensitivity analysis results are shown through the tornado graph in Figure 6. Each bar represents the CSFs considered in this study. The bar length indicates the influence of determinants over the target node, i.e. NZA (GeNIe, 2022). As evident from Figure 6, incentive schemes for organizations (CSF21), availability of professional expertise (CSF14), and

availability of funds for implementing sustainable practices (CSF12) are the influential CSFs. Findings from SODEA and strength of influence analysis support these results.

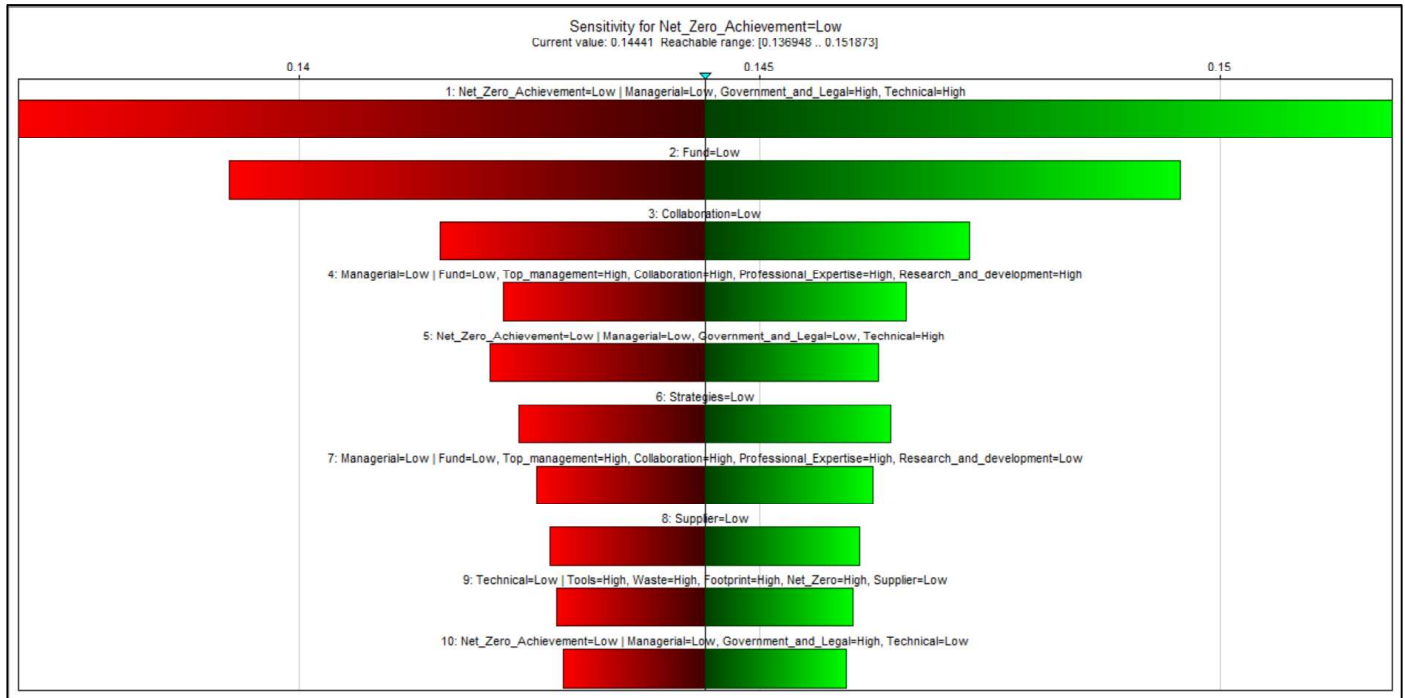


Figure 6. Sensitivity Analysis

5 Implications of the present research

The present research has a significant theoretical implication to the literature on net-zero emission and managerial implications to practitioners within the operations and supply chain domain. The present study complements the body of knowledge in the domain of not only environmental management but also operations and supply chain sustainability. This study offers novel insights into the CSFs of sustainable innovations that help for net-zero achievement in the context of the Indian manufacturing supply chains through a quantitative methodological approach. This study has noteworthy theoretical and methodological contributions to the state-of-the-art literature. Despite the criticality of sustainable innovations for NZA in supply chains, the literature on carbon neutrality and supply chain is still in its infancy to determine the critical factors to implement the sustainable innovations. The present study has made an early attempt in the literature to fill this gap. This study has successfully evaluated the influence of different CSFs of sustainable innovations over carbon neutrality achievement. Apart from this, a notable methodological contribution to the operations research literature is the application of the two-stage SODEA and BN methodology.

Existing studies have proved that combining ML techniques with optimization and MCDM methods strengthens the computation and helps overcome the shortcomings within one method (Dohale et al., 2022a; Kaya et al., 2023). Thus, the proposed SODEA and BN can effectively handle intricate problems with a big dataset and extend to other large-scale problems.

Alike its theoretical relevance, this study also offers practical implications. This study can be a guideline for manufacturing practitioners who are willing to implement sustainable innovation to engage with carbon-neutral supply chains. Managers may foster the key and significant CSFs in their organizations in a targeted manner to successfully execute and achieve decarbonization and net-zero emission practices within their operations and supply chains. Manufacturers can collaborate with each other to invent new sustainable innovations in line with NZA and make them available to their competitors, similar to Allbirds (Allbirds, 2022; Hobson and Hagan, 2019). Practitioners who are already engaged with sustainable innovations for NZA can utilize this study to compare the NZA achieved at their organizations with the present study's findings. This will help them comprehend the possible improvements in influential CSFs for attaining an optimal NZA. We also postulate that this research work can be insightful to practitioners to achieve operational excellence more generally through the interventions of sustainable innovations and practices in their operations and supply chain.

Apart from these implications, the present work has some recommendations in line with the sustainable development goals (SDGs). United nations defined SDGs as – “*the blueprint to achieve a better and more sustainable future for all*” (UN, 2020). The merging of SDGs and the pursuit of NZA carries significant ramifications within the manufacturing supply chain (Sofuoğlu and Kirikkaleli, 2022). Sustainable innovations are pivotal in steering manufacturing supply chains in striving towards the attainment of NZE and align closely with several SDGs, notably SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Organizations can significantly reduce their environmental footprint by integrating cleaner technologies, renewable energy sources, and eco-friendly materials (Ikram et al., 2021; Yadav et al., 2023). Complementing these efforts, embracing lean principles further bolsters these initiatives by optimizing resource utilization, minimizing waste, and enhancing operational efficiency.

Strategies encompassing digitalization, collaborative partnerships, and stringent carbon neutrality targets are also instrumental (Chauhan et al., 2022; Ma et al., 2024). In parallel, education, policy reinforcement, and a culture of continuous improvement form the bedrock

for nurturing a sustainable ethos across supply chains. This convergence of strategies propels advancements toward net-zero and fosters responsible production and consumption aligned with the SDGs (Cai and Choi, 2020; Gunawan et al., 2020; Yadav et al., 2023). By strategically aligning sustainable practices with the SDGs, the manufacturing supply chain addresses environmental concerns, drives economic growth, and cultivates social development. The infusion of sustainability in combination with lean (sustainable) into manufacturing supply chains significantly contributes to global endeavours to achieve net-zero emissions, steering us closer to a universally sustainable future.

6 Conclusion and Future Research Directions

The increment in manufacturing carbon footprint is becoming a nightmare for manufacturers as it is damaging not only the environment but also humanity presently and in the coming future. The goal to achieve “Carbon neutrality by 2050” has become the world's most urgent mission (Wang et al., 2021). Many nations have actively participated in this ambitious initiative of the United Nations to transform to carbon neutral by 2050. Governmental institutions are encouraging manufacturing industries to passionately work towards this agenda. Manufacturers are making their best efforts to reform their operations and supply chain in line with net-zero emissions. Different strategies have been conceived that help to achieve net-zero emissions. One such promising approach involves adopting sustainable and lean (sustainable) innovation that gives a boost to industries by delivering the benefits of both. Despite this fact, academia and practitioners are still stagnated to implement sustainable innovations in their business and supply chain level that can help them usher towards net-zero targets.

This research investigates and analyses the critical success factors that help manufacturers implement sustainable innovations to achieve carbon-neutral operations and supply chains. To this purpose, this study made an effort to answer the research questions mentioned in Section 1. We conducted a systematic literature review to address RQ 1, followed by a validity survey. We reviewed relevant literature to determine the essence of lean and sustainable innovations in the achievement of carbon-neutral supply chains and also presented some industrial examples to get a clearer understanding of the concept. Further, we identified 14 CSFs falling under 3 group CSFs that can help manufacturers implement sustainable innovations and convert their conventional operations and supply chain in a carbon-neutral manner. We also validated these 14 CSFs by utilizing the expertise of 125 manufacturing practitioners using a validity survey.

We adopted a two-stage approach comprising SODEA and BN methods to address RQ2. We evaluated all CSFs using these methods. Through SODEA, we determined the most crucial CSFs to implement sustainable innovations by computing their priority weights. Whereas BN is used to evaluate and predict the influence of each CSF on the overall net-zero achievement in Indian manufacturing supply chains. The findings from both methods complement each other. The results depict that incentive schemes for the organization (CSF21), availability of professional expertise (CSF14), and availability of funds for implementing sustainable practices (CSF12) are the key CSFs that show a significant level of influence on NZA. These CSFs are the ones in which manufacturing organizations can retain core competencies to achieve net-zero emissions in their operations and supply chains. Thus, embracing sustainable innovation by considering the significant CSFs for its implementation can enable businesses not only to reduce their carbon footprint but also to strengthen their competitiveness in the global market.

We propose a few directions for conducting future research. This study pertains to the analysis of CSFs in the manufacturing industry. However, a manufacturing industry can be spread across many environments, including – textile, automotive, plastic, machining, chemical, metal fabrication, etc. We expect that the findings may vary from environment to environment. Thus, prospective researchers can conduct future research to target a specific manufacturing environment and evaluate how these CSFs can influence the NZA. One of the most noticeable trade-offs observed in recent days is between the resilience and sustainability aspects within supply chains. The COVID-19 or the Suez Canal incident are the unanticipated disruptive events that occurred recently, which triggered the prominence of resilience in supply chains (Dohale et al., 2022b). Thus, researchers can rethink the Sustainable (sustainable + resilient) approach that can cater not only for sustainability but also for resilience in supply chains to develop resilient carbon neutrality within the operations and supply chains (Ambilkar et al., 2023; Dohale et al., 2023d). We further propose a technology adoption-based framework to understand how these sustainable innovations can play a mediating role in achieving net-zero targets by their successful adoption in various industries across different countries. Future studies can conduct a techno-economic analysis of the identified determinants of sustainable innovations of NZA to analyse the economic performance of manufacturing processes, products, or services.

Acknowledgement

We are immensely grateful to all the participating respondents who spent their time and efforts providing their opinions to us, which were instrumental in conducting this research work. We are also thankful to the anonymous reviewers and editors for providing their valuable feedback to help improve the quality of this research.

References

- Allbirds, 2022. We're changing so the climate doesn't [WWW Document]. URL <https://www.allbirds.com/pages/our-commitment> (accessed 4.13.22).
- Alonso, T., 2023. How Patagonia Became The Benchmark In Sustainable Clothing [WWW Document]. Strateg. Fact. by Cascade. URL <https://www.cascade.app/studies/patagonia-strategy-study>
- Ambilkar, P., Dohale, V., Gunasekaran, A., Bilolikar, V., 2022. Product returns management: a comprehensive review and future research agenda. *Int. J. Prod. Res.* 60, 3920–3944. <https://doi.org/10.1080/00207543.2021.1933645>
- Ambilkar, P., Verma, P., Das, D., 2023. Sustailient supplier selection using neutrosophic best–worst approach: a case study of additively manufactured trinkets. *Benchmarking An Int. J.* <https://doi.org/10.1108/BIJ-02-2023-0122>
- Asmae, M., Abdelali, E.-N., Brahim, H., 2022. Critical success factors of Lean implementation in Moroccan agro food supply chain, in: 2022 14th International Colloquium of Logistics and Supply Chain Management (LOGISTIQUA). IEEE, pp. 1–6. <https://doi.org/10.1109/LOGISTIQUA55056.2022.9938121>
- Ayyildiz, E., Taskin Gumus, A., 2021. A novel distance learning ergonomics checklist and risk evaluation methodology: A case of Covid- 19 pandemic. *Hum. Factors Ergon. Manuf. Serv. Ind.* 31, 397–411. <https://doi.org/10.1002/hfm.20908>
- Azadeh, A., Keramati, A., Songhori, M.J., 2009. An integrated Delphi/VAHP/DEA framework for evaluation of information technology/information system (IT/IS) investments. *Int. J. Adv. Manuf. Technol.* 45, 1233–1251. <https://doi.org/10.1007/s00170-009-2047-2>
- Bag, S., 2023. From resources to sustainability: a practice-based view of net zero economy implementation in small and medium business-to-business firms. *Benchmarking An Int. J.* <https://doi.org/10.1108/BIJ-01-2023-0056>
- Bai, C., Zhu, Q., Sarkis, J., 2022. Supplier portfolio selection and order allocation under carbon neutrality: Introducing a “Cool”ing model. *Comput. Ind. Eng.* 170, 108335. <https://doi.org/10.1016/j.cie.2022.108335>
- Bateman, A., Bonanni, L., 2019. What Supply Chain Transparency Really Means. *Harv. Bus. Rev.* 2–8.

- Bhattacharya, A., Nand, A., Castka, P., 2019. Lean-green integration and its impact on sustainability performance: A critical review. *J. Clean. Prod.* 236, 117697. <https://doi.org/10.1016/j.jclepro.2019.117697>
- Birasnav, M., Chaudhary, R., Henry Dunne, J., Bienstock, J., Seaman, C., 2022. Green supply chain management: A theoretical framework and research directions. *Comput. Ind. Eng.* 172, 108441. <https://doi.org/10.1016/j.cie.2022.108441>
- Bokrantz, J., Skoogh, A., Berlin, C., Stahre, J., 2017. Maintenance in digitalised manufacturing : Delphi-based scenarios for 2030. *Int. J. Prod. Econ.* 191, 154–169. <https://doi.org/10.1016/j.ijpe.2017.06.010>
- Bryman, A., Bell, E., 2015. *Business Research Methods*, 4th Edn. ed. Oxford University Press, New York.
- Cai, Y.-J., Choi, T.-M., 2020. A United Nations’ Sustainable Development Goals perspective for sustainable textile and apparel supply chain management. *Transp. Res. Part E Logist. Transp. Rev.* 141, 102010. <https://doi.org/10.1016/j.tre.2020.102010>
- Cao, K., Guo, Q., Xu, Y., 2023. Information sharing and carbon reduction strategies with extreme weather in the platform economy. *Int. J. Prod. Econ.* 255, 108683. <https://doi.org/10.1016/j.ijpe.2022.108683>
- Castillo, E., Gutiérrez, J.M., Hadi, A.S., 1997. *Expert Systems and Probabilistic Network Models*, Monographs in Computer Science. Springer New York, New York, NY. <https://doi.org/10.1007/978-1-4612-2270-5>
- Chauhan, C., Kaur, P., Arrawatia, R., Ractham, P., Dhir, A., 2022. Supply chain collaboration and sustainable development goals (SDGs). Teamwork makes achieving SDGs dream work. *J. Bus. Res.* 147, 290–307. <https://doi.org/10.1016/j.jbusres.2022.03.044>
- Chen, I.J., Paulraj, A., Lado, A.A., 2004. Strategic purchasing, supply management, and firm performance. *J. Oper. Manag.* 22, 505–523. <https://doi.org/10.1016/j.jom.2004.06.002>
- Chen, L., Msigwa, G., Yang, M., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.-S., 2022. Strategies to achieve a carbon neutral society: a review. *Environ. Chem. Lett.* 20, 2277–2310. <https://doi.org/10.1007/s10311-022-01435-8>
- Cherrafi, A., Garza-Reyes, J.A., Kumar, V., Mishra, N., Ghobadian, A., Elfezazi, S., 2018. Lean, green practices and process innovation: A model for green supply chain performance. *Int. J. Prod. Econ.* 206, 79–92. <https://doi.org/10.1016/j.ijpe.2018.09.031>
- Christopher, S., Vikram, M.P., Bakli, C., Thakur, A.K., Ma, Y., Ma, Z., Xu, H., Cuce, P.M., Cuce, E., Singh, P., 2023. Renewable energy potential towards attainment of net-zero energy buildings status – A critical review. *J. Clean. Prod.* 405, 136942. <https://doi.org/10.1016/j.jclepro.2023.136942>
- Cook, W.D., Kress, M., 1990. A Data Envelopment Model for Aggregating Preference Rankings. *Manage. Sci.* 36, 1302–1310. <https://doi.org/10.1287/mnsc.36.11.1302>
- COP26, 2021. The Glasgow climate pact. UN Climate Change Conference UK 2021, Glasgow, UK., in: *Cop26: The Glasgow Climate Pact*.

- de la Vega, M., Baez-Lopez, Y., Limon-Romero, J., Tlapa, D., Flores, D.L., Rodríguez Borbón, M.I., Maldonado-Macías, A.A., 2020. Lean manufacturing critical success factors for the transportation equipment manufacturing industry in Mexico. *IEEE Access* 8, 168534–168545. <https://doi.org/10.1109/ACCESS.2020.3023633>
- de Sousa Jabbour, A.B.L., Chiappetta Jabbour, C.J., Sarkis, J., Gunasekaran, A., Furlan Matos Alves, M.W., Ribeiro, D.A., 2019. Decarbonisation of operations management – looking back, moving forward: a review and implications for the production research community. *Int. J. Prod. Res.* 57, 4743–4765. <https://doi.org/10.1080/00207543.2017.1421790>
- Debnath, B., Shakur, M.S., Bari, A.B.M.M., Karmaker, C.L., 2023. A Bayesian Best–Worst approach for assessing the critical success factors in sustainable lean manufacturing. *Decis. Anal. J.* 6. <https://doi.org/10.1016/j.dajour.2022.100157>
- Dellink, R., Hwangi, H., Lanzi, E., Chateau, J., 2017. International trade consequences of climate change (No. 2017/01), OECD Trade and Environment Working Papers. <https://doi.org/10.1787/9f446180-en>
- Dohale, V., Akarte, M., Gunasekaran, A., Verma, P., 2022a. Exploring the role of artificial intelligence in building production resilience: learnings from the COVID-19 pandemic. *Int. J. Prod. Res.* 1–17. <https://doi.org/10.1080/00207543.2022.2127961>
- Dohale, V., Akarte, M.M., Gunasekaran, A., Verma, P., 2023a. Quantifying and Exhibiting the Congruence of Process Choice Criteria with Traditional and Additive Manufacturing Systems. *Prod. Plan. Control* 1–25.
- Dohale, V., Ambilkar, P., Bilollikar, V., Narkhede, B.E., Kumar, Ashwani, Kumar, Anil, 2023b. Evaluating circular economy and smart technology adoption barriers in the Indian textile and apparel industries using neutrosophic ISM. *Ann. Oper. Res.* <https://doi.org/10.1007/s10479-023-05651-5>
- Dohale, V., Ambilkar, P., Gunasekaran, A., Verma, P., 2022b. Supply chain risk mitigation strategies during COVID-19: exploratory cases of “make-to-order” handloom saree apparel industries. *Int. J. Phys. Distrib. Logist. Manag.* 52, 109–129. <https://doi.org/10.1108/IJPDLM-12-2020-0450>
- Dohale, V., Ambilkar, P., Kumar, A., Mangla, S.K., Bilollikar, V., 2023c. Analyzing the enablers of circular supply chain using Neutrosophic-ISM method: lessons from the Indian apparel industry. *Int. J. Logist. Manag.* 34, 611–643. <https://doi.org/10.1108/IJLM-03-2022-0141>
- Dohale, V., Gunasekaran, A., Akarte, M., Verma, P., 2021. An integrated Delphi-MCDM-Bayesian Network framework for production system selection. *Int. J. Prod. Econ.* 242, 108296. <https://doi.org/10.1016/j.ijpe.2021.108296>
- Dohale, V., Gunasekaran, A., Akarte, M.M., Verma, P., 2022c. 52 Years of manufacturing strategy: an evolutionary review of literature (1969–2021). *Int. J. Prod. Res.* 60, 569–594. <https://doi.org/10.1080/00207543.2021.1971788>
- Dohale, V., Kamble, S., Ambilkar, P., Gold, S., Belhadi, A., 2024. An integrated MCDM-ML approach for predicting the carbon neutrality index in manufacturing supply chains. *Technol. Forecast. Soc. Change* 201, 123243.

<https://doi.org/10.1016/j.techfore.2024.123243>

- Dohale, V., Verma, P., Gunasekaran, A., Amblikar, P., 2023d. COVID-19 and supply chain risk mitigation: a case study from India. *Int. J. Logist. Manag.* 34, 417–442. <https://doi.org/10.1108/IJLM-04-2021-0197>
- Farias, L.M.S., Santos, L.C., Gohr, C.F., Rocha, L.O., 2019. An ANP-based approach for lean and green performance assessment. *Resour. Conserv. Recycl.* 143, 77–89. <https://doi.org/10.1016/j.resconrec.2018.12.004>
- Fleith de Medeiros, J., Bisognin Garlet, T., Duarte Ribeiro, J.L., Nogueira Cortimiglia, M., 2022. Success factors for environmentally sustainable product innovation: An updated review. *J. Clean. Prod.* 345, 131039. <https://doi.org/10.1016/j.jclepro.2022.131039>
- Forgie, J., Carlson, A., 2018. Overcoming Organizational Barriers to Carbon Neutrality: Lessons from the UC Experience. *POLICY Br.* 9, 1–11.
- General Electric, 2021. Sustainability Report Building a World That Works for Tomorrow.
- GeNIe, 2022. GeNIe Modeler - USER MANUAL [WWW Document]. URL <https://support.bayesfusion.com/docs/GeNIe.pdf>
- Ghadge, A., Wurtmann, H., Seuring, S., 2020. Managing climate change risks in global supply chains: a review and research agenda. *Int. J. Prod. Res.* 58, 44–64. <https://doi.org/10.1080/00207543.2019.1629670>
- Ghobakhloo, M., Iranmanesh, M., Mubarak, M.F., Mubarik, M., Rejeb, A., Nilashi, M., 2022. Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values. *Sustain. Prod. Consum.* 33, 716–737. <https://doi.org/10.1016/j.spc.2022.08.003>
- Govindan, K., Muduli, K., Devika, K., Barve, A., 2016. Investigation of the influential strength of factors on adoption of green supply chain management practices: An Indian mining scenario. *Resour. Conserv. Recycl.* 107, 185–194. <https://doi.org/10.1016/j.resconrec.2015.05.022>
- Green, R.H., Doyle, J.R., Cook, W.D., 1996. Preference voting and project ranking using DEA and cross-evaluation. *Eur. J. Oper. Res.* 90, 461–472. [https://doi.org/10.1016/0377-2217\(95\)00039-9](https://doi.org/10.1016/0377-2217(95)00039-9)
- Gunawan, J., Permatasari, P., Tilt, C., 2020. Sustainable development goal disclosures: Do they support responsible consumption and production? *J. Clean. Prod.* 246, 118989. <https://doi.org/10.1016/j.jclepro.2019.118989>
- Hadi-Vencheh, A., Niazi-Motlagh, M., 2011. An improved voting analytic hierarchy process-data envelopment analysis methodology for suppliers selection. *Int. J. Comput. Integr. Manuf.* 24, 189–197. <https://doi.org/10.1080/0951192X.2011.552528>
- Hai, H.L., Liu, F.-H.F., 2007. Using the total vote-ranking to explore the pairwise comparison method for analytic hierarchy process. *J. Stat. Manag. Syst.* 10, 195–209. <https://doi.org/10.1080/09720510.2007.10701248>

- Hartini, S., Ciptomulyono, U., 2015. The Relationship between Lean and Sustainable Manufacturing on Performance: Literature Review. *Procedia Manuf.* 4, 38–45. <https://doi.org/10.1016/j.promfg.2015.11.012>
- Hegde, D.S. (Ed.), 2015. *Essays on Research Methodology*. Springer India, New Delhi. <https://doi.org/10.1007/978-81-322-2214-9>
- Hobson, J., Hagan, A., 2019. How Allbirds Turned Wool Sneakers into A Billion-Dollar Business [WWW Document]. URL <https://www.wbur.org/hereandnow/2019/09/10/allbirds-tim-brown-wool-sneakers> (accessed 4.14.22).
- Hohenstein, N.-O., Feisel, E., Hartmann, E., Giunipero, L., 2015. Research on the phenomenon of supply chain resilience. *Int. J. Phys. Distrib. Logist. Manag.* 45, 90–117. <https://doi.org/10.1108/IJPDLM-05-2013-0128>
- Horowitz, C.A., 2016. Paris Agreement. *Int. Leg. Mater.* 55, 740–755. <https://doi.org/10.1017/S0020782900004253>
- Hosseini, S., Barker, K., 2016a. A Bayesian network model for resilience-based supplier selection. *Int. J. Prod. Econ.* 180, 68–87. <https://doi.org/10.1016/j.ijpe.2016.07.007>
- Hosseini, S., Barker, K., 2016b. Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports. *Comput. Ind. Eng.* 93, 252–266. <https://doi.org/10.1016/j.cie.2016.01.007>
- Hosseini, S., Ivanov, D., 2021. A multi-layer Bayesian network method for supply chain disruption modelling in the wake of the COVID-19 pandemic. *Int. J. Prod. Res.* <https://doi.org/10.1080/00207543.2021.1953180>
- Hosseini, S., Ivanov, D., Dolgui, A., 2020. Ripple effect modelling of supplier disruption: integrated Markov chain and dynamic Bayesian network approach. *Int. J. Prod. Res.* 58, 3284–3303. <https://doi.org/10.1080/00207543.2019.1661538>
- Hosseini, S., Sarder, M., 2019. Development of a Bayesian network model for optimal site selection of electric vehicle charging station. *Electr. Power Energy Syst.* 105, 110–122. <https://doi.org/10.1016/j.ijepes.2018.08.011>
- Ikram, M., Ferasso, M., Sroufe, R., Zhang, Q., 2021. Assessing green technology indicators for cleaner production and sustainable investments in a developing country context. *J. Clean. Prod.* 322, 129090. <https://doi.org/10.1016/j.jclepro.2021.129090>
- ITF, 2016. The Carbon Footprint of Global Trade [WWW Document]. URL <https://www.itf-oecd.org/sites/default/files/docs/cop-pdf-06.pdf>
- Janssens, C., Havlík, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., Leclère, D., Ohrel, S., Ragnauth, S., Schmid, E., Valin, H., Van Lipzig, N., Maertens, M., 2020. Global hunger and climate change adaptation through international trade. *Nat. Clim. Chang.* 10, 829–835. <https://doi.org/10.1038/s41558-020-0847-4>
- Kamble, S.S., Gunasekaran, A., Kumar, V., Belhadi, A., Foropon, C., 2021. A machine learning based approach for predicting blockchain adoption in supply Chain. *Technol.*

- Forecast. Soc. Change 163, 120465. <https://doi.org/10.1016/j.techfore.2020.120465>
- Kannan, D., Solanki, R., Kaul, A., Jha, P.C., 2022. Barrier analysis for carbon regulatory environmental policies implementation in manufacturing supply chains to achieve zero carbon. *J. Clean. Prod.* 358, 131910. <https://doi.org/10.1016/j.jclepro.2022.131910>
- Kaya, R., Salhi, S., Spiegler, V., 2023. A novel integration of MCDM methods and Bayesian networks: the case of incomplete expert knowledge. *Ann. Oper. Res.* 320, 205–234. <https://doi.org/10.1007/s10479-022-04996-7>
- Khan, F., Ali, Y., 2022. Implementation of the circular supply chain management in the pharmaceutical industry. *Environ. Dev. Sustain.* <https://doi.org/10.1007/s10668-021-02007-6>
- Khan, S.A.R., Yu, Z., Umar, M., Tanveer, M., 2022. Green capabilities and green purchasing practices: A strategy striving towards sustainable operations. *Bus. Strateg. Environ.* 31, 1719–1729. <https://doi.org/10.1002/bse.2979>
- Kumar, N., Mathiyazhagan, K., 2020. Modeling the Interrelationship of Critical Success Factors Adoption of Sustainable Lean Manufacturing Using DEMATEL Approach, in: *Lecture Notes in Mechanical Engineering*. pp. 31–45. https://doi.org/10.1007/978-981-15-1071-7_4
- Kumar, N., Mathiyazhagan, K., Mathivathanan, D., 2020. Modelling the interrelationship between factors for adoption of sustainable lean manufacturing: a business case from the Indian automobile industry. *Int. J. Sustain. Eng.* 13, 93–107. <https://doi.org/10.1080/19397038.2019.1706662>
- Ladhad, A., Parrish, K., 2013. The role of lean practices for zero net energy retrofits, in: *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*. pp. 855–864.
- Li, H., Hao, Y., Xie, C., Han, Y., Wang, Z.-R., 2023. Emerging technologies and policies for carbon-neutral transportation. *Int. J. Transp. Sci. Technol.* 12, 329–334. <https://doi.org/10.1016/j.ijtst.2022.09.002>
- Liu, F.-H.F., Hai, H.L., 2005. The voting analytic hierarchy process method for selecting supplier. *Int. J. Prod. Econ.* 97, 308–317. <https://doi.org/10.1016/j.ijpe.2004.09.005>
- Luqmani, A., Leach, M., Jesson, D., 2017. Factors behind sustainable business innovation: The case of a global carpet manufacturing company. *Environ. Innov. Soc. Transitions* 24, 94–105. <https://doi.org/10.1016/j.eist.2016.10.007>
- Ma, J., Yang, L., Wang, D., Li, Y., Xie, Z., Lv, H., Woo, D., 2024. Digitalization in response to carbon neutrality: Mechanisms, effects and prospects. *Renew. Sustain. Energy Rev.* 191, 114138. <https://doi.org/10.1016/j.rser.2023.114138>
- Mahapatra, S.K., Schoenherr, T., Jayaram, J., 2021. An assessment of factors contributing to firms' carbon footprint reduction efforts. *Int. J. Prod. Econ.* 235, 108073. <https://doi.org/10.1016/j.ijpe.2021.108073>
- Majumdar, A., Sinha, S.K., 2019. Analyzing the barriers of green textile supply chain

- management in Southeast Asia using interpretive structural modeling. *Sustain. Prod. Consum.* 17, 176–187. <https://doi.org/10.1016/j.spc.2018.10.005>
- Majumdar, A., Sinha, S.K., Shaw, M., Mathiyazhagan, K., 2021. Analysing the vulnerability of green clothing supply chains in South and Southeast Asia using fuzzy analytic hierarchy process. *Int. J. Prod. Res.* 59, 752–771. <https://doi.org/10.1080/00207543.2019.1708988>
- Malhotra, M.K., Grover, V., 1998. An assessment of survey research in POM: from constructs to theory. *J. Oper. Manag.* 16, 407–425. [https://doi.org/10.1016/S0272-6963\(98\)00021-7](https://doi.org/10.1016/S0272-6963(98)00021-7)
- Mathiyazhagan, K., Gnanavelbabu, A., Kumar, N., Agarwal, V., 2022. A framework for implementing sustainable lean manufacturing in the electrical and electronics component manufacturing industry: An emerging economies country perspective. *J. Clean. Prod.* 334. <https://doi.org/10.1016/j.jclepro.2021.130169>
- Mishra, R., Singh, R., Govindan, K., 2022. Net-zero economy research in the field of supply chain management: a systematic literature review and future research agenda. *Int. J. Logist. Manag.* <https://doi.org/10.1108/IJLM-01-2022-0016>
- Mohib, A., En-nadi, A., Herrou, B., 2023. PRIORITISING CRITICAL SUCCESS FACTORS OF LEAN IMPLEMENTATION IN THE FOOD SUPPLY CHAIN. *Proc. Eng. Sci.* 5, 119–132. <https://doi.org/10.24874/pes05.01.012>
- Muthu, S.S., 2019. Circular Economy in Textiles and Apparel, Circular Economy in Textiles and Apparel: Processing, Manufacturing, and Design. Elsevier. <https://doi.org/10.1016/C2017-0-03221-4>
- Naranjo, F., Menor, L.J., Johnson, P.F., 2023. Lean supply chain management: a contextual contingent reconceptualization and Delphi method study. *Int. J. Oper. Prod. Manag.* <https://doi.org/10.1108/IJOPM-07-2022-0436>
- Netland, T.H., 2016. Critical success factors for implementing lean production: The effect of contingencies. *Int. J. Prod. Res.* 54, 2433–2448. <https://doi.org/10.1080/00207543.2015.1096976>
- Noguchi, H., Ogawa, M., Ishii, H., 2002. The appropriate total ranking method using DEA for multiple categorized purposes. *J. Comput. Appl. Math.* 146, 155–166. [https://doi.org/10.1016/S0377-0427\(02\)00425-9](https://doi.org/10.1016/S0377-0427(02)00425-9)
- Nyangchak, N., 2022. Emerging green industry toward net-zero economy: A systematic review. *J. Clean. Prod.* 378, 134622. <https://doi.org/10.1016/j.jclepro.2022.134622>
- Oelze, N., 2017. Sustainable Supply Chain Management Implementation—Enablers and Barriers in the Textile Industry. *Sustainability* 9, 1435. <https://doi.org/10.3390/su9081435>
- Orji, I.J., Liu, S., 2020. A dynamic perspective on the key drivers of innovation-led lean approaches to achieve sustainability in manufacturing supply chain. *Int. J. Prod. Econ.* 219, 480–496. <https://doi.org/10.1016/j.ijpe.2018.12.002>
- Patagonia, 2023. Everything we make has an impact on the planet [WWW Document]. URL <https://www.patagonia.com/our-footprint/> (accessed 3.20.23).

- Pishchulov, G., Trautrimis, A., Chesney, T., Gold, S., Schwab, L., 2019. The Voting Analytic Hierarchy Process revisited: A revised method with application to sustainable supplier selection. *Int. J. Prod. Econ.* 211, 166–179. <https://doi.org/10.1016/j.ijpe.2019.01.025>
- Qureshi, K.M., Mewada, B.G., Alghamdi, S.Y., Almakayeel, N., Qureshi, M.R.N., Mansour, M., 2022. Accomplishing Sustainability in Manufacturing System for Small and Medium-Sized Enterprises (SMEs) through Lean Implementation. *Sustain.* 14. <https://doi.org/10.3390/su14159732>
- Rayer, Q., Jenkins, S., Walton, P., 2022. Defining Net-Zero and Climate Recommendations for Carbon Offsetting, in: *Business and Policy Solutions to Climate Change*. pp. 13–35. https://doi.org/10.1007/978-3-030-86803-1_2
- Remenyi, D., Williams, B., Money, A., Swartz, E., 1998. *Doing research in business and management: an introduction to process and method*. Sage Publications, London.
- Rezaei, J., 2015. Best-worst multi-criteria decision-making method. *Omega (United Kingdom)* 53, 49–57. <https://doi.org/10.1016/j.omega.2014.11.009>
- Rötzer, S., Wilberg, J., Lindemann, U., 2016. Lean innovation methods: Application & evaluation during a student project, in: *Proceedings of International Design Conference, DESIGN*. pp. 473–482.
- Saaty, T.L., 2008. Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* 1, 83–98.
- Sandberg, E., Krook-Riekkola, A., 2022. The impact of technology availability on the transition to net-zero industry in Sweden. *J. Clean. Prod.* 363, 132594. <https://doi.org/10.1016/j.jclepro.2022.132594>
- Saunders, M.N.K., Lewis, P., Thornhill, A., 2020. *Research Methods for Business Students*, 8th Edn. ed. Pearson, New York, NY, USA.
- Saunders, M.N.K., Lewis, P., Thornhill, A., 2009. *Research Methods for Business Students*. Pearson, New Delhi, India.
- Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technol. Anal. Strateg. Manag.* 20, 537–554. <https://doi.org/10.1080/09537320802292651>
- Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* 16, 1699–1710. <https://doi.org/10.1016/j.jclepro.2008.04.020>
- Shali, D.N., 1986. Pragmatism and Social Interactionism. *Am. Sociol. Rev.* 51, 9–29.
- Sindhvani, R., Singh, P.L., Behl, A., Afridi, M.S., Sammanit, D., Tiwari, A.K., 2022. Modeling the critical success factors of implementing net zero emission (NZE) and promoting resilience and social value creation. *Technol. Forecast. Soc. Change* 181, 121759. <https://doi.org/10.1016/j.techfore.2022.121759>
- Sipahi, S., Timor, M., 2010. The analytic hierarchy process and analytic network process: an

- overview of applications. *Manag. Decis.* 48, 775–808. <https://doi.org/10.1108/00251741011043920>
- Sofuoğlu, E., Kirikkaleli, D., 2022. Towards achieving net zero emission targets and sustainable development goals, can long-term material footprint strategies be a useful tool? *Environ. Sci. Pollut. Res.* 30, 26636–26649. <https://doi.org/10.1007/s11356-022-24078-2>
- Soltanifar, M., Hosseinzadeh Lotfi, F., 2011. The voting analytic hierarchy process method for discriminating among efficient decision making units in data envelopment analysis. *Comput. Ind. Eng.* 60, 585–592. <https://doi.org/10.1016/j.cie.2010.12.016>
- Thanki, S.J., Thakkar, J., 2018. Interdependence analysis of lean-green implementation challenges: a case of Indian SMEs. *J. Manuf. Technol. Manag.* 29, 295–328. <https://doi.org/10.1108/JMTM-04-2017-0067>
- Timmermans, K., 2023. How supply chain sustainability helps unlock resilience and growth [WWW Document]. Accenture. URL <https://www.accenture.com/za-en/insights/supply-chain-operations/supply-chains-key-unlocking-net-zero-emissions> (accessed 4.27.23).
- TOYOTA, 2022. North American Environmental Sustainability Report 2022 [WWW Document]. Toyota North Am. Environ. Sustain. Rep. URL https://www.toyota.com/content/dam/tusa/environmentreport/downloads/2022NAER_Final.pdf
- Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A.K., Sharma, S., Singh, J., Pimenov, D.Y., Giasin, K., 2021. An Innovative Agile Model of Smart Lean–Green Approach for Sustainability Enhancement in Industry 4.0. *J. Open Innov. Technol. Mark. Complex.* 7, 215. <https://doi.org/10.3390/joitmc7040215>
- Udokporo, C.K., Anosike, A., Lim, M., Nadeem, S.P., Garza-Reyes, J.A., Ogbuka, C.P., 2020. Impact of Lean, Agile and Green (LAG) on business competitiveness: An empirical study of fast moving consumer goods businesses. *Resour. Conserv. Recycl.* 156. <https://doi.org/10.1016/j.resconrec.2020.104714>
- UN, 2022. For a livable climate: Net-zero commitments must be backed by credible action [WWW Document]. Clim. Action. URL <https://www.un.org/en/climatechange/net-zero-coalition#:~:text=What is net zero%3F,oceans and forests for instance.> (accessed 12.21.23).
- UN, 2021. From Mission Zero to Climate Take Back: How Interface is Transforming its Business to Have Zero Negative Impact | Global [WWW Document]. United Nations Clim. Chang. URL <https://unfccc.int/climate-action/momentum-for-change/climate-neutral-now/interface>
- UN, 2020. Take Action for the Sustainable Development Goals [WWW Document]. Sustain. Dev. Goals. URL <https://www.un.org/sustainabledevelopment/sustainable-development-goals/> (accessed 12.21.23).
- UN, 2015. THE 17 GOALS - Sustainable Development Goals [WWW Document]. URL <https://sdgs.un.org/goals> (accessed 4.13.22).

- Unilever, 2021. Unilever Sustainable Living Plan 2010 to 2020 [WWW Document]. URL <https://www.unilever.com/files/92ui5egz/production/16cb778e4d31b81509dc5937001559f1f5c863ab.pdf>
- Vimal, K.E.K., Kumar, A., Sunil, S.M., Suresh, G., Sanjeev, N., Kandasamy, J., 2022. Analysing the challenges in building resilient net zero carbon supply chains using Influential Network Relationship Mapping. *J. Clean. Prod.* 379, 134635. <https://doi.org/10.1016/j.jclepro.2022.134635>
- Virmani, N., Agarwal, S., Raut, R.D., Paul, S.K., Mahmood, H., 2022. Adopting net-zero in emerging economies. *J. Environ. Manage.* 321, 115978. <https://doi.org/10.1016/j.jenvman.2022.115978>
- VOGUE, 2021. Fashion is chasing carbon neutrality. Carbon positive is better [WWW Document]. URL <https://www.voguebusiness.com/sustainability/fashion-is-chasing-carbon-neutrality-carbon-positive-is-better-allbirds-reformation-nicholas-kirkwood>
- Wang, Fang, Harindintwali, J.D., Yuan, Zhizhang, Wang, M., Wang, Faming, Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., Chang, S.X., Zhang, L., Rinklebe, J., Yuan, Zuoqiang, Zhu, Q., Xiang, L., Tsang, D.C.W., Xu, L., Jiang, X., Liu, J., Wei, N., Kästner, M., Zou, Y., Ok, Y.S., Shen, J., Peng, D., Zhang, W., Barceló, D., Zhou, Y., Bai, Z., Li, B., Zhang, B., Wei, K., Cao, H., Tan, Z., Zhao, L., He, X., Zheng, J., Bolan, N., Liu, X., Huang, C., Dietmann, S., Luo, M., Sun, N., Gong, J., Gong, Y., Brahushi, F., Zhang, T., Xiao, C., Li, X., Chen, W., Jiao, N., Lehmann, J., Zhu, Y.-G., Jin, H., Schäffer, A., Tiedje, J.M., Chen, J.M., 2021. Technologies and perspectives for achieving carbon neutrality. *Innov.* 2, 100180. <https://doi.org/10.1016/j.xinn.2021.100180>
- Wang, J., Zhao, C., 2022. Reducing carbon footprint in a resilient supply chain: examining the critical influencing factors of process integration. *Int. J. Prod. Res.* <https://doi.org/10.1080/00207543.2022.2063088>
- WTO, 2021. The carbon content of international trade [WWW Document]. World Trade Organ. URL https://www.wto.org/english/news_e/news21_e/clim_03nov21-4_e.pdf
- Wu, P., Feng, Y., 2012. USING LEAN PRACTICES TO IMPROVE CURRENT CARBON LABELLING SCHEMES FOR CONSTRUCTION MATERIALS— A GENERAL FRAMEWORK. *J. Green Build.* 7, 173–191. <https://doi.org/10.3992/jgb.7.1.173>
- Wu, X., Zhu, J., Wang, X., 2021. A review on carbon reduction analysis during the design and manufacture of solid wood furniture. *BioResources* 16, 6212–6230. <https://doi.org/10.15376/biores.16.3.6212-6230>
- Wuest, T., Weimer, D., Irgens, C., Thoben, K., Wuest, T., Weimer, D., Irgens, C., Thoben, K., 2016. Machine learning in manufacturing: advantages, challenges, and applications. *Prod. Manuf. Res.* 4, 23–45. <https://doi.org/10.1080/21693277.2016.1192517>
- Yadav, S., Samadhiya, A., Kumar, A., Majumdar, A., Garza-Reyes, J.A., Luthra, S., 2023. Achieving the sustainable development goals through net zero emissions: Innovation-driven strategies for transitioning from incremental to radical lean, green and digital technologies. *Resour. Conserv. Recycl.* 197, 107094. <https://doi.org/10.1016/j.resconrec.2023.107094>

- Yunus, R., Yang, J., 2012. Critical sustainability factors in industrialised building systems. *Constr. Innov.* 12, 447–463. <https://doi.org/10.1108/14714171211272216>
- Zhan, Y., Tan, K.H., Ji, G., Chung, L., Chiu, A.S.F., 2018. Green and lean sustainable development path in China: Guanxi, practices and performance. *Resour. Conserv. Recycl.* 128, 240–249. <https://doi.org/10.1016/j.resconrec.2016.02.006>
- Zhang, A., Tay, H.L., Alvi, M.F., Wang, J.X., Gong, Y., 2022. Carbon neutrality drivers and implications for firm performance and supply chain management. *Bus. Strateg. Environ.* <https://doi.org/10.1002/bse.3230>
- Zhu, Q., Geng, Y., Sarkis, J., Lai, K., 2011. Evaluating green supply chain management among Chinese manufacturers from the ecological modernization perspective. *Transp. Res. Part E Logist. Transp. Rev.* 47, 808–821. <https://doi.org/10.1016/j.tre.2010.09.013>
- Zou, C., Xue, H., Xiong, B., Zhang, G., Pan, S., Jia, C., Wang, Y., Ma, F., Sun, Q., Guan, C., Lin, M., 2021. Connotation, innovation and vision of “carbon neutrality.” *Nat. Gas Ind. B* 8, 523–537. <https://doi.org/10.1016/j.ngib.2021.08.009>

List of Appendix

Appendix 1. Details of Respondents Participated in Conducting Validatory Survey, SODEA, and BN

Particulars	Content	No. of Experts	%
Academic Qualification	Ph.D.	8	6%
	Post-Graduate	94	75%
	Graduate	23	18%
Designation	Vice President	7	6%
	General Manager - Manufacturing	37	30%
	Operations Manager	59	47%
	Junior Level Operations Managers	22	18%
Work Experience	26-30+ Years	21	17%
	21-25 Years	24	19%
	16-20 Years	37	30%
	11-15 Years	25	20%
	05-10 Years	18	14%

Appendix 2. Questionnaire for Validatory Survey

On the Scale of 1 to 5, rate whether the identified CSFs are applicable in the Indian Manufacturing Supply Chains. Where, 1 refers to “Strongly Disagree” while 5 refers to “Strongly Agree”.

Group CSFs	Sub-CSFs	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process					
	Availability of Funds for implementing sustainable practices					
	Collaboration among stakeholders					
	Availability of professional expertise					
	Focus on research and development activities to adopt innovative technological solutions					
Government and Legal Factors (CSF2)	Incentive schemes for organisations					
	Promoting sustainability and CO2 emission reduction initiatives					
	Strategic planning and effective roadmap					
	Law and certification					
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals					
Technical Factors (CSF3)	Maintaining sustainability in waste management					
	Carbon footprint reduction					
	Adoption of eco-innovation for achieving net-zero goals					
	Availability of sustainable supplier					

Appendix 3. Responses of Validatory Survey

Group CSFs	Sub-CSFs	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Mean Score
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process	0	3	22	19	81	4.4
	Availability of Funds for implementing sustainable practises	0	0	7	24	94	4.7
	Collaboration among stakeholders	0	4	9	79	33	4.1
	Availability of professional expertise	0	2	17	84	22	4.0
	Focus on research and development activities to advent innovative technological solutions	4	9	14	61	37	3.9
Government and Legal Factors (CSF2)	Incentive schemes for organisations	0	0	0	21	104	4.8
	Promoting sustainability and CO2 emission reduction initiatives	0	2	4	69	50	4.3
	Strategic planning and effective roadmap	15	9	16	54	31	3.6
	Law and certification	7	16	9	61	32	3.8
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	0	0	9	12	104	4.8
Technical Factors (CSF3)	Maintaining sustainability in waste management	0	0	4	25	96	4.7
	Carbon footprint reduction	0	0	18	88	19	4.0
	Adoption of eco-innovation for achieving net-zero goals	0	0	0	34	91	4.7
	Availability of sustainable supplier	4	5	0	27	89	4.5

Appendix 4. Description of CSFs of Sustainable Innovations for Carbon Neutrality

Critical Success Factor	Description	Reference
Adequate support from top management in the implementation process	Skilful and proficient guidance is provided by individuals in positions of authority within an organization. In the context of reforming traditional practices and beliefs, effective leadership and management play a crucial role in initiating and driving radical changes that aim to improve overall performance by implementing sustainable practices to achieve net-zero emission.	(Asmae et al., 2022; de la Vega et al., 2020; de Sousa Jabbour et al., 2019; Debnath et al., 2023; Mathiyazhagan et al., 2022; Mohib et al., 2023; Netland, 2016; Qureshi et al., 2022; Thanki & Thakkar, 2018; Virmani et al., 2022)
Availability of funds for implementation of sustainable practices	Financial capabilities encompass the organization's investment of capital to develop and implement sustainable manufacturing strategies to achieve net-zero emissions. These capabilities involve allocating funds for activities such as employee training, building internal teams with diverse skills, and engaging external consultants.	(de la Vega et al., 2020; de Sousa Jabbour et al., 2019; Fleith de Medeiros et al., 2022; Qureshi et al., 2022; Thanki & Thakkar, 2018; Virmani et al., 2022)
Collaboration among stakeholders	The active engagement, communication, and coordination among stakeholders to achieve a sustainable manufacturing supply chain.	(de Sousa Jabbour et al., 2019; Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022; Virmani et al., 2022)
Availability of Professional Expertise	The proficiency and expertise of employees play a crucial role in the success of organizational strategies. Employees' active involvement and participation enable the organization to achieve its predetermined business goals. Investing in employee training can enhance their skills and performance, leading to overall organizational improvement.	(Asmae et al., 2022; de la Vega et al., 2020; Debnath et al., 2023; Mathiyazhagan et al., 2022; Mohib et al., 2023; Netland, 2016; Thanki & Thakkar, 2018; Tripathi et al., 2021; Zhan et al., 2018)
Focus on research and development activities to advent innovative technological solutions	It conducts scientific research, experiments, and investigations to discover novel ideas and concepts that can lead to the development of innovative technological solutions for sustainable manufacturing and circular supply chains to achieve net-zero emissions.	(Tripathi et al., 2021; Virmani et al., 2022; Dohale et al., 2023b)

Critical Success Factor	Description	Reference
Incentive schemes for organization	Government support through a range of incentives, financial assistance, and policies aimed at encouraging the implementation of quality and productivity improvement practices and tools to achieve net-zero emissions. This support encompasses various initiatives, including technology transfer and development assistance, subsidies, and taxation policies. These measures are essential conditions that contribute to the advancement of sustainable practices across different sectors.	(de Sousa Jabbour et al., 2019; Debnath et al., 2023; Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022; Qureshi et al., 2022; Thanki & Thakkar, 2018)
Promoting sustainability & CO2 Emission reduction initiatives	The efforts and actions are undertaken to encourage and support practices that contribute to environmental sustainability and reduce carbon dioxide (CO2) emissions. This involves promoting and implementing strategies, policies, and activities to minimise the negative impact of human activities on the environment and mitigate climate change.	(de Sousa Jabbour et al., 2019; Qureshi et al., 2022)
Strategic planning and effective roadmap	The process of developing a comprehensive and well-defined strategy to eliminate or offset greenhouse gas emissions, resulting in a carbon-neutral or net-zero emissions state. It involves setting long-term targets and developing a clear roadmap that outlines the steps, actions, and initiatives necessary to transition towards a sustainable and low-carbon future.	(Asmae et al., 2022; de la Vega et al., 2020; Mohib et al., 2023; Netland, 2016; Qureshi et al., 2022; Tripathi et al., 2021; Virmani et al., 2022; Wu et al., 2021)
Law and Certification	The regulatory frameworks, policies, and certification systems established by governments, industry bodies, and organizations to promote and enforce sustainable practices and emission reduction targets.	(de Sousa Jabbour et al., 2019; Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022)

Critical Success Factor	Description	Reference
Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	Organizations can identify opportunities, implement effective measures, and continuously improve their operations to achieve net-zero emissions. It empowers them to make informed decisions, optimize resource utilization, minimize waste, and contribute to a sustainable and low-carbon future.	(Netland, 2016; Qureshi et al., 2022; Tripathi et al., 2021; Zhan et al., 2018)
Maintaining sustainability in waste management	Implementing practices and strategies that ensure environmentally responsible and sustainable handling, treatment, and disposal of waste materials to achieve net-zero emissions.	(Ambilkar et al., 2022; de la Vega et al., 2020; Debnath et al., 2023; Qureshi et al., 2022; Thanki and Thakkar, 2018; Udokporo et al., 2020; Zhan et al., 2018)
Carbon footprint reduction	The deliberate and systematic efforts to minimize or eliminate greenhouse gas (GHG) emissions associated with human activities, aiming to achieve net-zero emissions. It involves quantifying and mitigating the amount of carbon dioxide (CO2) and other GHG emissions released into the atmosphere from various sources, such as energy consumption, transportation, industrial processes, and waste management.	(Debnath et al., 2023; Virmani et al., 2022; Wu et al., 2021)
Adoption of eco-innovation for achieving Net-zero target	Implementing and utilizing environmentally friendly and innovative practices, energy-saving technologies, and processes to reduce greenhouse gas emissions and achieve a net-zero emission state.	(Fleith de Medeiros et al., 2022; Mathiyazhagan et al., 2022; Virmani et al., 2022; Wu et al., 2021; Zhan et al., 2018)
Availability of sustainable supplier	The presence of suppliers who prioritize sustainability in their operations, products, and services by reducing processes impacting the environment, promoting sustainable practices, and offering sustainable and low-carbon solutions.	(de la Vega et al., 2020; Debnath et al., 2023; Mathiyazhagan et al., 2022; Mohib et al., 2023; Qureshi et al., 2022; Thanki & Thakkar, 2018; Virmani et al., 2022)

Appendix 5. Questionnaire for SODEA

Vote the CSFs according to their relative importance to achieve carbon neutrality or net-zero achievement in the Indian Manufacturing Supply Chains in the corresponding ranks. Kindly tick the ranking place suitable for the corresponding CSFs based on their importance.

Group CSF	1st Place	2nd Place	3rd Place	4th Place	5th Place
Managerial (CSF1)					
Government and Legal (CSF2)					
Technical (CSF3)					

Managerial (CSF1)	1st Place	2nd Place	3rd Place	4th Place	5th Place
Adequate Support from top management in the implementation process (CSF11)					
Availability of Funds for implementing sustainable practices (CSF12)					
Collaboration among stakeholders (CSF13)					
Availability of professional expertise (CSF14)					
Focus on research and development activities to advent innovative technological solutions (CSF15)					

Government and Legal (CSF2)	1st Place	2nd Place	3rd Place	4th Place
Incentive schemes for organisations (CSF21)				
Promoting sustainability and CO2 emission reduction initiatives (CSF22)				
Strategic planning and effective roadmap (CSF23)				
Law and certification (CSF24)				

Technical (CSF3)	1st Place	2nd Place	3rd Place	4th Place	5th Place
Know-how of the sustainable and lean tools and techniques to achieve net-zero goals (CSF31)					
Maintaining sustainability in waste management (CSF32)					
Carbon footprint reduction (CSF33)					
Adoption of eco-innovation for achieving net-zero goals (CSF34)					
Availability of sustainable supplier (CSF35)					

Appendix 6. Questionnaire for Bayesian Network

On a scale of 1 to 6, rate the influence of CSFs of sustainable innovations on the net-zero achievement in the Indian Manufacturing Supply Chains. Where 1 refers to “Extremely Low” while 6 refers to “Extremely High”.

Group CSFs	Sub-CSFs	Extremely Low (1)	Very Low (2)	Low (3)	High (4)	Very High (5)	Extremely High (6)
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process						
	Availability of Funds for implementing sustainable practices						
	Collaboration among stakeholders						
	Availability of professional expertise						
	Focus on research and development activities to adopt innovative technological solutions						
Government and Legal Factors (CSF2)	Incentive schemes for organisations						
	Promoting sustainability and CO2 emission reduction initiatives						
	Strategic planning and effective roadmap						
	Law and certification						
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals						
Technical Factors (CSF3)	Maintaining sustainability in waste management						
	Carbon footprint reduction						
	Adoption of eco-innovation for achieving net-zero goals						
	Availability of sustainable supplier						

Appendix 7. Survey for collecting prior probability data for Bayesian Network (BN)

Group CSFs	Sub-CSFs	Low						High			Total Responses	Low	High
		1	2	3	4	5	6						
		EL	VL	L	H	VH	EH						
Managerial Factors (CSF1)	Adequate Support from top management in the implementation process	1	3	16	24	27	54	125	0.16	0.84			
	Availability of Funds for implementing sustainable practices	0	0	26	32	51	16	125	0.208	0.792			
	Collaboration among stakeholders	1	0	19	44	51	10	125	0.16	0.84			
	Availability of professional expertise	0	0	4	16	91	14	125	0.032	0.968			
	Focus on research and development activities to adopt innovative technological solutions	7	11	39	38	19	11	125	0.456	0.544			
Government and Legal Factors (CSF2)	Incentive schemes for organisations	0	4	2	13	64	42	125	0.048	0.952			
	Promoting sustainability and CO2 emission reduction initiatives	0	2	9	25	28	61	125	0.088	0.912			
	Strategic planning and effective roadmap	14	9	21	31	21	29	125	0.352	0.648			
	Law and certification	2	8	21	36	41	17	125	0.248	0.752			
	Know-how of the sustainable and lean tools and techniques to achieve net-zero goals	0	0	2	19	24	80	125	0.016	0.984			
Technical Factors (CSF3)	Maintaining sustainability in waste management	0	0	1	6	27	91	125	0.008	0.992			
	Carbon footprint reduction	0	0	2	2	29	92	125	0.016	0.984			
	Adoption of eco-innovation for achieving net-zero goals	0	1	2	29	41	52	125	0.024	0.976			
	Availability of sustainable supplier	0	2	26	12	24	61	125	0.224	0.776			

**Sustainable Innovations for Net-Zero Achievement in the Manufacturing Sector:
Analysis of Critical Factors**

Author Details:

Vishwas Dohale ^{a,1} (ORCID: 0000-0002-7895-3309), dohale.vishwas@gmail.com

Priya Ambilkar ^{b,1} (ORCID: 0000-0002-9195-1746), Priya.Ambilkar.2017@nitie.ac.in

Sachin Kumar Mangla ^{c,d,*} (ORCID: 0000-0001-7166-5315), sachinmangl@gmail.com

Balkrishna Eknath Narkhede ^b (ORCID: 0000-0002-9277-3005), benarkhede@nitie.ac.in

Affiliations:

- a. Business School, Dublin City University, Dublin 9, Ireland
- b. Department of Operations and Supply Chain Management (O&SCM), Indian Institute of Management, Mumbai, India
- c. Operations Management, Jindal Global Business School, O. P. Jindal Global University, Haryana, India
- d. Knowledge Management & Business Decision Making, University of Plymouth, UK

(¹ These authors are the first authors and have contributed equally)

(* The corresponding Authors)

No conflict of interest is reported among the authors.

COVER LETTER

Co-Editors-in-Chief: Prof. Cecília Maria Villas Bôas de Almeida,
Journal of Cleaner Production

Subject: Declaration about the manuscript titled “Critical Factors to Sustaileanant Innovations for Net-Zero Achievement in the Manufacturing Supply Chains”

Dear Editor,

With due regards, this to certify that the reported work in the manuscript entitled **“Critical Factors to Sustaileanant Innovations for Net-Zero Achievement in the Manufacturing Supply Chains”** submitted for possible publication in your esteemed Journal “Journal of Cleaner Production” is original unpublished research paper.

Abstract

The entire world is gaining tremendous awareness about creating fewer carbon emissions to save the environment for future generations. Global economies are putting enormous efforts into minimizing their carbon footprints and, in turn, ushering towards carbon neutrality, also known as net-zero emission. In the present study, we seek the expertise of manufacturing experts to understand how sustainable and lean (sustaileanant) innovations can act as enablers and help achieve net-zero in manufacturing supply chains to make them eco-friendly. We initially determined the critical success factors (CSFs) of sustaileanant innovations that can help achieve net-zero emissions in manufacturing supply chains and validated through manufacturing experts using a validity survey. We further utilized a two-stage method comprising strong ordering data envelopment analysis (SODEA) and machine learning (ML) based Bayesian network (BN) to understand the significant CSFs that can help bring change in the existing carbon-dominated manufacturing sector to achieve a net-zero goal. We collected data from 125 experts from the Indian manufacturing sector to conduct SODEA-BN methods.

The results from the present study depict that incentive schemes for organizations, availability of professional expertise, and availability of funds for implementing sustainable practices are crucial for organizations to transform and achieve carbon neutrality. This study will guide practitioners and academicians in understanding the critical sustainable factors for building the successful net-zero economy.

Keywords – Sustainable Innovations, Net-Zero, Supply Chain Management, Strong Ordering Data Envelopment Analysis, Machine Learning, Bayesian Network

Thank you very much for your kind support.

We are very much looking forward to your kind advice on the same.

With Warm Regards

Dr. Sachin K. Mangla

Corresponding Author

Knowledge Management & Business Decision Making

Plymouth Business School – Plymouth, United Kingdom, PL4 8AA

Email: sachinmangl@gmail.com

Sachin.kumar@plymouth.ac.uk

CRedit Author Statement

We submit CRedit author(s) statement outlining individual contributions as follows:

Sustainable Innovations for Net-Zero Achievement in the Manufacturing Sector: Analysis of Critical Factors

Vishwas Dohale: Conceptualization, Data curation, Methodology, Formal analysis, and Writing-original draft

Priya Ambilkar: Conceptualization, Data curation, Methodology, Formal analysis, and Writing-original draft

Sachin Kumar Mangla: Conceptualization, Writing- original draft and editing, Resources, and Project administration

Balkrishna Eknath Narkhede: Conceptualization, Data curation, Methodology, Formal analysis, and Writing- original draft

(All authors have contributed equally)

Highlights

**Critical Factors to Sustainable Innovations for Net-Zero Achievement in
the Manufacturing Supply Chains**

- Identified 14 CSFs of sustainable and lean (sustainable) innovations for NZA
- Evaluated CSFs of sustainable innovations using integrated SODEA-BN methods
- Indian manufacturing supply chain context is considered for determining NZA
- Influence of CSFs of sustainable innovations on NZA is computed
- Implications and recommendations are provided in line with SDGs