Cleaner Engineering and Technology 24 (2025) 100882

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Identifying enablers for a circular healthcare supply chain: An integrated fuzzy DEMATEL-MMDE approach with hesitant information

Deepak Agrawal [a], Sumit Gupta [b,**], Chandni Dusad [c,d], M.L. Meena [a], G.S. Dangayach [a], Sandeep Jagtap [e,f,*]

[a] Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur, India
[b] Department of Mechanical Engineering, Amity School of Engineering and Technology, Amity University Uttar Pradesh, Noida, India
[c] Department of Management Studies, University of Engineering & Management, Jaipur, India
[d] Department of Management Studies, Graphic Era (Deemed to Be University), Dehradun, India
[e] Sustainable Manufacturing Systems Centre, School of Aerospace, Transport & Manufacturing, Cranfield University, Cranfield, MK43 0AL, UK
[f] Division of Engineering Logistics, Department of Mechanical Engineering Sciences, Faculty of Engineering, Ole Römers Väg 1, M-Building, Lund University, Lund, 22363, Sweden

ARTICLE INFO

Keywords:
Healthcare supply chain
Enablers
Circular economy
DEMATEL
MMDE
Fuzzy linguistic term sets
Alpha level sets

ABSTRACT

Over the past decade, the healthcare industries have been facing the issue of resource scarcity due to socio-political wars, the COVID-19 pandemic, the luxury lifestyles of people, and the prevalence of single-use medical devices. The circular economy (CE) can be vital in accommodating the evolving patient and provider demands. The CE defies the conventional take-make-dispose process and advocates for optimized resource use throughout its entire lifecycle. Finding the critical enabler for a circular supply chain in the Indian healthcare sector is urgently needed because the CE is still nascent in developing nations like India. This paper identifies the enablers of a circular healthcare supply chain (CHSC) through a comprehensive analysis of cause and effect, interrelationships, and priorities using integrated alpha-level sets based on the fuzzy DEMATEL-MMDE approach with hesitant information. Experts' opinions were gathered using a triangular fuzzy linguistic scale, incorporating hesitant information to minimize data vagueness. The results of this study offer valuable insights into various enablers, emphasizing their criticality and interdependence, thereby benefiting healthcare organizations aiming to implement circular supply chains. Additionally, the findings will assist policymakers in creating policies to accelerate the adoption of CE practices in the healthcare industry.

1. Introduction

Healthcare supply chain management (HSCM) encompasses a wide range of procedures and components to ensure the timely production, transportation, and administration of pharmaceuticals and medical supplies to patients (Torrado and Barbosa-Póvoa, 2022). HSCM involves managing the flow of medical devices and information among stakeholders, including manufacturers, suppliers, distributors, retailers, and end users (hospitals, medical centers, customers, and patients) (Tyagi, 2023). Socio-political wars, the COVID-19 pandemic, and the luxury lifestyles of people have increased the demand for healthcare devices (Ferrari et al., 2023). Lifestyle-related disorders such as diabetes, stroke, cancer, and obesity are becoming more common due to demographic changes, rapid urbanization, and resource constraints (Siddiqui and Singh, 2020). The growing population has further exacerbated the situation. According to UN estimates, India is expected to have 1.45 billion people by 2028, making it the most populated country in the world. Limited raw materials and other resources make it challenging to meet demand within the prescribed time frame and at a reasonable price. Another major factor for the increased supply is the prevalence of single-use medical devices, disposed of after use, adversely affecting the environment.

* Corresponding author. Sustainable Manufacturing Systems Centre, School of Aerospace, Transport & Manufacturing, Cranfield University, Cranfield, MK43 0AL, UK.
** Corresponding author.
E-mail addresses: deepakagrawal210@gmail.com (D. Agrawal), sgupta20@amity.edu (S. Gupta), khandelwalchandni19@gmail.com (C. Dusad), mlmeena.mech@mnit.ac.in (M.L. Meena), sandeep.jagtap@tlog.lth.se (S. Jagtap).

https://doi.org/10.1016/j.clet.2025.100882
Received 27 July 2024; Received in revised form 24 December 2024; Accepted 2 January 2025
Available online 3 January 2025
2666-7908/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

The CE can play a vital role in bridging the gap between demand and supply and finding new ways to reutilize single-use medical devices. The CE defies the conventional take-make-dispose process and advocates for optimized resource use throughout its entire lifecycle and beyond that. Adopting CE principles is expected to transform supply chain operations to become more sustainable, converting the conventional supply chain into a circular supply chain (CSC) (Lahane and Kant, 2021a; Lahane and Kant, 2021b). When CE principles are applied to the healthcare supply chain (HSC), it is called the CHSC. Resource utilization can be optimized using concepts such as 6R and the sharing economy. Although the inclusion of CE principles in supply chain management is gaining significant attention, its role in the HSC must be thoroughly investigated (Dohale et al., 2023). Implementing a CE in developing countries like India is urgently needed to cope with the increasing demand for medical devices. This paper models and analyses the enablers of the CHSC, providing policymakers and managers with insights to implement CE practices in their industries. To achieve this, the following research questions and objectives are framed.

RQ1: What are the enablers for implementing the CHSC?
RQ2: What is the cause-and-effect relationship among these enablers?
RQ3: What is the priority of the identified enablers and policy suggestions to policymakers, researchers, and industrial practitioners?

To address these research questions, enablers for implementing the CHSC have been identified through a literature review and brainstorming sessions with the authors. A hybrid approach of fuzzy DEMATEL and MMDE has been used to analyze enablers, incorporating hesitant experts' information. The alpha-level sets theory is also used to acquire and analyze the information provided by the experts.

The study objectives formulated to address these research questions are:

RO1: Identifying and enumerating the enablers for implementing the CHSC with the help of experts and a literature review.

RO2: Implementing a hesitant fuzzy DEMATEL-MMDE approach to examine and construct a cause-and-effect relationship among the enablers of the CHSC.

RO3: Prioritizing the identified enablers of the CHSC and recommending the theoretical implications and policy suggestions to policymakers, researchers, and industrial practitioners.

This research contributes to the knowledge of implementing CE enablers in the healthcare sector. The study highlights how CE principles can address the scarcity of healthcare devices and elaborates on the interrelationships and criticality of various enablers to facilitate the use of CE in the healthcare sector. The research focuses on developing countries like India, where recent government initiatives such as the 'Production Linked Incentive Scheme for Promoting Domestic Manufacturing of Medical Devices,' 'Scheme for Promotion of Medical Devices Parks,' 'PM Gati Shakti National Master Plan (NMP),' 'National Logistics Policy (NLP),' 'Make in India,' 'Atmanirbhar Bharat (self-reliant India),' and 'Digital India' programs make it easier to implement CE. This research will be valuable to healthcare professionals and policymakers in devising strategies to implement CE in their industries.

This research paper is organized as follows: Section 2 reviews the literature on enablers of the CHSC, the fuzzy DEMATEL approach, and the MMDE method. Section 3 discusses the chosen research methodology. Section 4 presents the modeling and analysis of enablers. Section 5 includes the results and discussion. Section 6 covers the research implications. Finally, Section 7 addresses the policy implications, limitations, and future scope.

2. Literature review

A systematic literature search was conducted for articles in English-language journals to identify research gaps, focusing mainly on circular supply chain publications. The Scopus database was selected for this search using the following keywords: ((TITLE-ABS-KEY ({Supply Chain} OR {Circular economy} OR {Reverse Logistics}) AND TITLE-ABS-KEY (enablers OR facilitator OR driver OR precedents) OR TITLE-ABS-KEY ({Circular Economy} AND {Supply Chain})). A total of 331 documents were found using these criteria. The articles were further refined by excluding subject areas irrelevant to the objective, such as physics and astronomy, arts and humanities, agriculture and biological sciences, and chemistry. Additionally, only articles, review papers, and book chapters were considered. This refinement process resulted in 227 documents selected for abstract reading. After reviewing the abstracts, 82 articles were taken for further consideration. Nine more articles related to hesitant fuzzy, fuzzy DEMATEL, and MMDE methods were also included. Thus, 91 articles were selected to identify the research gaps. This extensive literature review revealed that no study had been published focusing on analyzing enablers of the CHSC in the Indian context.

This section also reviews the literature of previous articles relevant to the identified research questions. In this context, the earlier studies related to enablers of the CHSC and the role of alpha-level based Integrated fuzzy DEMATEL-MMDE approach with Hesitant Information are highlighted.

2.1. Recent literature on enablers

Studying the enablers required to implement circular supply chain management is critical. By analyzing and prioritizing these enablers, focus areas can be identified. The subsequent paragraphs discuss various research papers involving enablers in the supply chain.

In a recent study, the enablers of sustainable healthcare performance were prioritized using Grey Delphi and Grey AHP approaches to improve the cost-effectiveness and quality of HSC services. The study categorized 16 enablers according to three bottom lines of sustainability: economic, social, and environmental. The study's conclusions determined which factors should have the highest priority according to the top three rankings: green packaging of pharmaceutical and essential items, healthcare by-product management system, coordinating and facilitating green suppliers in the HSC, and healthcare by-product management system. "HCSC infrastructure, continuous improvement programs on greening the HCSC," and "managing HCSC risks and crises" were among the enablers with the lowest priority (Hossain and Thakur, 2024). In another study, researchers analyzed the barriers to building a 3D printing-enabled local medical supply chain. The study determined that the main forces behind developing 3DP-enabled localized supply chain ecosystems were the necessity for a shift in company strategy, strong stakeholder participation, and prompt assistance from the local government (Kamble et al., 2023; Adel et al., 2024).

Tseng et al. (2022) categorized a set of CSC collaboration attributes from earlier research, developed and improved theories to prioritize and explain the interrelationships among attributes, and proposed a cause-and-effect framework using the hybrid fuzzy DEMATEL and ANP process. The characteristics included reverse logistics policies, circularity in business models, connections in a circular supply chain, vision and learning in circularity, and information technology facilitating cooperation. The results showed that vision and learning in circularity had the most substantial impact on the connection in a CSC and circularity in a business model compared with the other causal aspects. One study categorized supply chain enablers as financial, operational, strategy-related, and supply chain-related (Heeres et al., n.d.). They concluded that the most potent enablers are those related to the supply chain, such as enhanced transparency, traceability, and supplier collaboration.

Kayikci et al. (2022) discovered the smart and sustainable circular supply chain (SSCSC) enablers in achieving the SDGs in LMIC (low- and middle-income countries) through stakeholder theory using hybrid MCDM techniques BWM and TOPSIS. The results from BWM showed economic sustainability as the best driver for achieving SDGs, and

TOPSIS analyzed SDG16 (peace, justice, and strong institutions) as the top SDG supported by enablers. Moreover, a study on barriers and enablers of the CE in single-use healthcare devices was performed. They examined the perspectives of different stakeholders as consumers of devices (committing to high-value care, recognizing reuse, updating procurement policies), original equipment manufacturers (performance-based business models, circular product design), and regulators, accreditors, and professional standards organizations (regulations and emission targets, right to repair, regulatory environment to drive circularity, environmental product declaration, and extended producer responsibility). However, their study did not use empirical research to prioritize the enablers and barriers (Macneill et al., 2020). By systematically reviewing the literature and expert opinions, ten enablers have been identified for adopting a CHSC in the Indian context. These are listed in Table 1 and discussed as follows.

2.1.1. Extended producer responsibility (C1)

Extended producer responsibility is an environmentally favorable policy where manufacturers and importers are responsible for their products throughout their life cycle and beyond (Kalmykova et al., 2018). Extended producer responsibility schemes can be adopted to close the loop, promoting the collection, processing, and recycling of end products or materials from users to create a CE (Richter & Koppejan, 2016). Policymakers can draft guidelines for extended producer responsibility in the healthcare industry to facilitate resource life extension (Macneill et al., 2020).

2.1.2. Favorable national policies for the medical device sector (C2)

The National Medical Device Policy 2023, introduced by the Government of India, includes a comprehensive framework based on coordinated strategies for sustainable development and growth of the healthcare sector. The policy is supported by initiatives such as the 'Production Linked Incentive Scheme for Promoting Domestic Manufacturing of Medical Devices,' 'Scheme for Promotion of Medical Devices Parks,' 'PM Gati Shakti National Master Plan (NMP),' 'National Logistics Policy (NLP),' 'Make in India,' 'Atmanirbhar Bharat (self-reliant India),' and 'Digital India' programs, which motivate domestic production and investments. The main objective of this policy is to become a global leader in the medical device sector by capturing 10–12% of the worldwide market over the next 25 years. The policy aims to achieve access, universality, affordability, quality, patient-centered care, preventive and promotive health, security, research, and innovation while developing a skilled workforce. Strategies to promote the medical device sector include regulatory streamlining, facilitating R&D innovations, enabling infrastructure, human resource development, creating awareness, and attracting investment.

2.1.3. Adoption of the 6R concept to boost the economy (C3)

Initially, the CE was based on the 3R principle (reduction, reuse, and recycling) and focused on saving materials and energy (Yuan et al., 2006). Over the subsequent decades, the 6R concept, which includes recovery, redesign, and remanufacture, was introduced (Govindan and Hasanagic, 2018). Implementing the 6R principles can reduce dependency on raw materials and energy, open markets for secondary products, provide economic benefits to industries, and improve overall sustainability. In healthcare, the 6R principles can be applied to medical devices for better resource utilization and resilience.

2.1.4. Market share gain and competitiveness (C4)

In the current era of globalization, competition among firms has increased. The demand for high-quality products through optimized processes and resources has also risen. For long-term sustainability, continuous improvement is necessary (Patel et al., 2021). Environmentally conscious customers are increasingly demanding circular products for a sustainable future. By adopting circular practices, firms can gain a competitive edge, increase market share, and build a positive image among environmentally conscious customers.

Table 1
Identified enablers of CHSC.

S. No.	Enabler	References
1	Extended Producer Responsibility (C1)	(Hart et al., 2019; Macneill et al., 2020; Upadhyay and Shukla, 2024)
2	Favorable national policies for the medical device sectors (C2)	User defined
3	Adoption of the 6R concept to boost the economy (C3)	(Bentahar et al., 2023; Bhattacharya et al., 2024; Dwivedi et al., 2023; Govindan and Bouzon, 2018; Govindan and Hasanagic, 2018; Hart et al., 2019; Jia et al., 2020; Kayikci et al., 2022b; S. A. Khan et al., 2022; Lahane and Kant, 2021a; Macneill et al., 2020; Moktadir et al., 2018; Mondal et al., 2023a; Orji et al., 2022; Patel et al., 2021; Qazi and Appolloni, 2022; Sabale et al., 2023; Swarnakar et al., 2023; Tseng et al., 2024; Tura et al., 2019; Upadhyay and Shukla, 2024; Yadav et al., 2020)
4	Market share gain and competitiveness (C4)	(Dwivedi et al., 2023; Erol et al., 2023; Govindan and Bouzon, 2018; Hossain and Thakur, 2022; Jia et al., 2020; S. A. Khan et al., 2022; Moktadir et al., 2018; Mondal et al., 2023b; Orji et al., 2022; Sharma et al., 2020; Swarnakar et al., 2023; Tseng et al., 2024; Tura et al., 2019; Yadav et al., 2020)
5	Incentive scheme for product return back (C5)	(Govindan and Bouzon, 2018; Nag et al., 2021; Sabale et al., 2023)
6	Pressure from Stakeholders for International Agreements (C6)	(Beheshti et al., 2023; Calzolari et al., 2021; Fobbe and Hilletofth, 2023; Govindan and Bouzon, 2018; Hussain et al., 2018; Jia et al., 2020; Mondal et al., 2023b; Orji et al., 2022; Swarnakar et al., 2023; Tseng et al., 2024; Tura et al., 2019)
7	Applicability of Corporate Social Responsibility (C7)	(Dwivedi et al., 2023; Kayikci et al., 2022b; S. A. Khan et al., 2022; Lahane et al., 2022; Lahane and Kant, 2021a; Mondal et al., 2023a, 2023b; Sabale et al., 2023)
8	Transfer of technology and knowledge Management (C8)	(Agrawal et al., 2023; Fobbe and Hilletofth, 2023; Govindan and Bouzon, 2018; Jia et al., 2020; Mondal et al., 2023b; Swarnakar et al., 2023; Tseng et al., 2024; Vishwakarma et al., 2023)
9	Revamping packaging and procurement practices to encourage recycling (C9)	(Bressanelli et al., 2021; Dwivedi et al., 2023; Hossain and Thakur, 2022; Jia et al., 2020; F. Khan and Ali, 2022; Lahane et al., 2022; Macneill et al., 2020; Moktadir et al., 2018; Patel et al., 2021; Qazi and Appolloni, 2022; Yadav et al., 2020)
10	Long term strategic planning for circularity (C10)	(Erol et al., 2023; Hart et al., 2019; S. Khan et al., 2022; Lahane et al., 2022; Lahane and Kant, 2021a; Mondal et al., 2023a; Orji et al., 2022; Patel et al., 2021; Qazi and Appolloni, 2022; Sabale et al., 2023; Tura et al., 2019; Upadhyay and Shukla, 2024)

2.1.5. Incentive scheme for product return (C5)

Sometimes, healthcare devices are used briefly and can be reused by others if adequately maintained. Manufacturers can launch incentive schemes for users to return products within a specified interval. After receiving product returns, manufacturers can recover rare and precious metals, reducing dependency on virgin material manufacturing, enhancing resource availability, and positively impacting circularity

(Sharma et al., 2020). Another concern is the safe disposal of medical equipment, which can be managed through an incentive scheme for product returns (Mura et al., 2020). Incentive schemes can also reduce the excessive use of single-use medical devices, promoting a more CE.

2.1.6. Pressure from stakeholders for international agreements (C6)

Due to increased awareness and attention from stakeholders towards sustainability, industries are pressured to become more competitive in the market (Jakhar et al., 2019). Organizations must adhere to international agreements, such as the UN SDG 2030, to sustain themselves in the global market (Upadhyay and Shukla, 2024). The collective pressure from external stakeholders (international regulators, governments, healthcare institutes, and end-users) can force healthcare industries to implement CE initiatives (Khan et al., 2022).

2.1.7. Applicability of corporate social responsibility (C7)

Corporate social responsibility (CSR) involves efforts by firms to promote the welfare of internal stakeholders (management and employees) and external stakeholders (customers, society, and the environment) while conducting business ethically (Aheleroff et al., 2021). Strategic CSR can help organizations sustain themselves long-term, facilitate a CE, and attract more potential customers without compromising quality (Hina et al., 2022; Nagariya et al., 2021). Empirical analysis of HSC 4.0, incorporating CE principles, shows that CSR and Industry 4.0 can help firms transition from a linear to a circular model (Daú et al., 2019).

2.1.8. Transfer of technology and knowledge management (C8)

Knowledge management is crucial in healthcare, enabling organizations to build procedures for training, risk management, and crisis recovery through education (Betto and Garengo, 2023). By providing current data and reliable information, knowledge management capabilities allow medical institutions to make sensible choices and promptly address client demands. Businesses can locate new consumers and devise strategies to retain them using data mining, IT integration, and customer analysis. Effective customer knowledge management enables organizations to respond to client requests promptly and appropriately (Dastjerdi et al., 2023). Technology transfer among various stakeholders can further facilitate the adoption of the CE.

2.1.9. Revamping packaging and procurement practices to encourage recycling (C9)

Green packaging and procurement minimize harmful environmental and societal effects (Moktadir et al., 2018). Despite limited profit margins in developing countries, implementing a recognition and reward system can promote green packaging and procurement (Yadav et al., 2020). Awareness campaigns among stakeholders about using recyclable or biodegradable packaging instead of plastic can accelerate circularity (Gue et al., 2020). Reusing packaging materials and employing efficient packaging design practices can reduce the carbon footprint, favoring circularity (Kalmykova et al., 2018; Baddley and Rasheed, 2023).

2.1.10. Long-term strategic planning for circularity (C10)

Considering the ecological, economic, and social advantages of adopting a circular supply chain in the long run, organizations should establish long-term planning for circularity rather than focusing solely on short-term financial benefits. Involving all internal and external stakeholders in strategic planning will eliminate potential conflicts (Khan et al., 2022). The planning should align with the firm's goals for sustainable future growth by considering environmental policies and globalization (Patel et al., 2021). The involvement of top management can act as a catalyst for implementing strategic planning and investments to achieve circularity, giving the firm a competitive edge (Kayikci et al., 2022a,b).

2.2. The role of alpha-level based integrated fuzzy DEMATEL-MMDE approach with hesitant information

Multi-criteria decision-making (MCDM) is a tool for determining and comparing various solutions to problems involving multi-variable multi-response optimization. It considers all the possible alternative solutions without overlooking any pivot element and then provides the best possible solution. MCDM promotes stakeholders' involvement by taking their opinions directly from them (Alshahrani et al., 2024). Many researchers have used various techniques like fuzzy AHP, fuzzy FUCOM, and fuzzy BWM to decide the priorities of factors, but all these techniques are lacking in categorizing the factors into cause-and-effect categories and determining the interrelationship between the factors (Sankar et al., 2024; Mahmudah et al., 2024; Tseng et al., 2024). The fuzzy DEMATEL provides different dimensions (Classifying in causal and effect groups, the strength of correlations between factors, interrelationship between the factors) to analyze the factors as confirmed by various researchers (Fan et al., 2024; Zhang et al., 2023; Eti et al., 2024).

When dealing with imprecise and uncertain situations, seeking expert opinions using a linguistic scale rather than quantitative values is essential. Computing with words (CWW) is critical in this context. To enhance the CWW decision-making process, the hesitant fuzzy linguistic term set (HFLTS) was introduced. This method facilitates expert decision-making when there is hesitation between several linguistic terms. HFLTS provides greater flexibility to decision-makers, offering many options and closely aligning with the human cognitive model. The fuzzy envelope transforms multiple linguistic terms obtained from hesitant information, thereby reducing vagueness and uncertainty in the decision-making process (Liu and Rodríguez, 2014). It is also observed that, due to inclusion of 'zeros' in the HFLTS, it is very difficult to use in other techniques like fuzzy FUCOM due to the divisibility of weights (which makes it indeterminate problem). But, in the DEMATEL method, the HFLTS can be easily used for critical analysis of the factors with hesitancy.

In the conventional fuzzy DEMATEL method, fuzzy numbers are directly converted into crisp values, which can result in the loss of essential information provided by the experts. Defuzzification may contradict the experts' opinions because crisp values cannot incorporate the uncertainties inherent in fuzzy details. To overcome this shortcoming, the concept of α-level sets is considered. Using α-level sets, the final DEMATEL matrix consists of three matrices: lower, middle, and upper (Fan et al., 2024). These three matrices provide different dimensions to interpret the interrelationship between the factors. Regarding the many outcomes at each alpha level, it is simple and straightforward to determine the trend and variations among the factors, and the particular result can be selected according to the specified problem (Zhang et al., 2023).

Determining the threshold value is critical in the DEMATEL method for drawing interrelationship maps, which provides more detailed insight into the factors. Various methods exist to determine the threshold value, such as taking the arithmetic mean or a combination of the arithmetic mean and standard deviation ($\mu + n\sigma$), where the value of n is adjusted from 1 to 3 for convenience. Other methods include the Lenth method (Hsieh et al., 2016) and the constricted information space method (Apaydın and Aladağ, 2022). However, these methods require the researcher to decide on arbitrary values, which can create unnecessary confusion. The MMDE method eliminates this shortcoming by considering the concept of maximum mean de-entropy (Li and Tzeng, 2009). Thus, the study uses an alpha-level-based integrated Fuzzy DEMATEL-MMDE approach with Hesitant Information to analyze CHSC enablers.

2.3. Research gaps

The literature review revealed that many researchers have focused on identifying enablers in the HSC (Hossain and Thakur, 2024; Macneill

et al., 2020). However, no published study has considered CE in the Indian HSC. Furthermore, no published study has used the α set-based fuzzy DEMATEL-MMDE method with hesitant information to prioritize enablers of a CHSC. Consequently, the research uniquely employs this method to identify critical enablers and their interrelationships.

3. Research methodology

First, the research questions and objectives were identified. Subsequently, a systematic literature review was conducted to identify CE enablers in the healthcare sector. We conducted three group brainstorming sessions with all the authors using electronic media. In the first session the enablers have classified into four categories: Environmental & Regulatory, Management, Social & Technological, and Economical. In the second session, each category further divided into four subcategories after combining and deleting some repetitive and similar enablers of CHCSC. For example: environmental product declaration, committing high value care, increase the value of product by increasing quality, right to repair and standardization of warranty for recycled, remanufactured, and used products combined to form a sub category as Extended Producer Responsibility as shown by Appendix 1. After the second session, the bifurcation of enablers again checked and confirmed in the third session. After these rigorous brainstorming sessions resulting in sixteen enablers of CHSC. As in the DEMATEL method, the cause effect relationship between each enabler is to be identified, a continuous list of sixteen enablers was formed. These sixteen enablers again checked and verified to medical officers of five Northern India hospitals for further refinement and valuable insight according to the latest healthcare practices in the Indian hospitals. The interviews were conducted using electronic media for further screening and finalization of the enablers. Some of the enablers were again combined and deleted a for example: Government support for R&D is already provided by the Government in favorable national policy for medical device sector, so the enabler 'Government support for R&D was deleted. Likewise, three enablers ISO 14001 certification, international agreements such as SDG 2030 and pressure from stakeholders were combined to form an enabler named as 'Pressure from stakeholders for international agreements'. After getting the feedback from medical officers, ten enablers were found critical and considered for further study, as shown in Appendix 2. For the micro-study of the enablers, the enablers were limited to 10, which is also justified by the recent research studies performed with the DEMATEL method (Singh and Bhanot, 2020; Khan et al., 2024; Torkayesh et al., 2024).

After finalization of enablers a questionnaire was prepared, which was again verified by the same medical officer team for the pilot study. The suggestion for incorporating an example to explain the use of hesitant fuzzy scale for giving opinions was incorporated. The process of screening and finalization of enablers were clearly explained to all the experts for verification purpose. The experts are asked to give their opinion on the degree of causal relationship of the enablers to one another based on the following specific questions: "To what extent does 'row enabler i' influence 'column enabler j'. The responses were collected using electronic media individually from all the experts. Researcher also provided the clarification about the enablers and used hesitant fuzzy scale whenever requested. Most academicians generally agree that the most effective way to deal with group decision-making involves five to seven people (Wang et al., 2022). Therefore, five experts from industry and academia were finalized to collect their views, and they have more than ten years of experience. The brief introduction is given in Table 3. The sample size of experts is small, but it is satisfactory as, firstly, an HFLTS has been taken in the study, which provides greater flexibility to decision-makers, offering many options and closely aligning with the human cognitive model. Secondly, the information provided by the experts may be lost when dealing with crisp value, so the alpha set-based approach is used, which will provide three matrices: lower bound, upper bound, and information matrices. Thirdly, the number of experts is also supported by some previous studies that dealt with the fuzzy DEMATEL approach (Song and Cao, 2017; Kazancoglu et al., 2018; Khan et al., 2019, 2024; Parmar and Desai, 2020; Menon and Ravi, 2021). After selecting experts, the enablers were analyzed using the proposed method, as drawn in Fig. 1 and discussed in the next section.

Table 3
Expert's profile involving in hesitant fuzzy DEMATEL method.

Expert	Job Designation	Experience in years	Qualification	Professional field
1	Senior Medical Officer	19	Postgraduate	Govt. Hospital
2	Manager	12	Postgraduate	Healthcare Industry
3	Supply Chain manager	11	Graduate	Healthcare Industry
4	Professor	18	Ph. D.	Academia
5	Assistant Professor	16	Ph. D.	Academia

4. Modelling and analysis of enablers

The following section elaborates on the stepwise algorithm, starting with hesitant information and fuzzy DEMATEL to MMDE, as shown in Fig. 1.

Step I: Expert opinion collection.

The developed questionnaire collects expert opinions on a fuzzy linguistic scale (Table 4). To include hesitancy, the experts can choose comparative linguistic expressions (CLE) as at least, at most, in between, along with fuzzy linguistic terms. For computation, CLE is transformed into a related HFLTS (see example 1).

Example 1. The four possible CLEs S_{ll_1}, S_{ll_2}, S_{ll_3} could be the following ones,

S_{ll_1} = between MI and VHI
S_{ll_2} = at least HI
S_{ll_3} = at most LI
S_{ll_4} = LI

Solution: Now, the above CLE S_{ll} can be transformed into HFLTS H_S as follows:

$$H_{s1} = \{MI, HI, VHI\}$$

$$H_{s2} = \{HI, VHI, EHI\}$$

$$H_{s3} = \{ELI, VLI, LI\}$$

$$H_{s4} = \{LI\}$$

The collected response in the form of CLE is shown in Table 5 (by Expert I) and Appendix 3 (by other experts).

Step II: Information Transformation.

After obtaining H_S, the corresponding fuzzy envelopes were determined using the fuzzy envelope function. The envelope function $env_F(.)$, is given in equation (1)

$$env_F(H_s) = \Gamma(a, b, c, d) \tag{1}$$

Where $\Gamma(a, b, c, d)$ is a trapezoidal fuzzy membership function corresponding to a trapezoidal fuzzy number (a, b, c, d) (see supplementary material for further information) (Liu and Rodríguez, 2014). The opinion transformation matrices are shown in Table 6 (for expert I) and Appendix 4 (for other experts).

Step III: Information Aggregation.

Now, using equation (2), five information transformation matrices

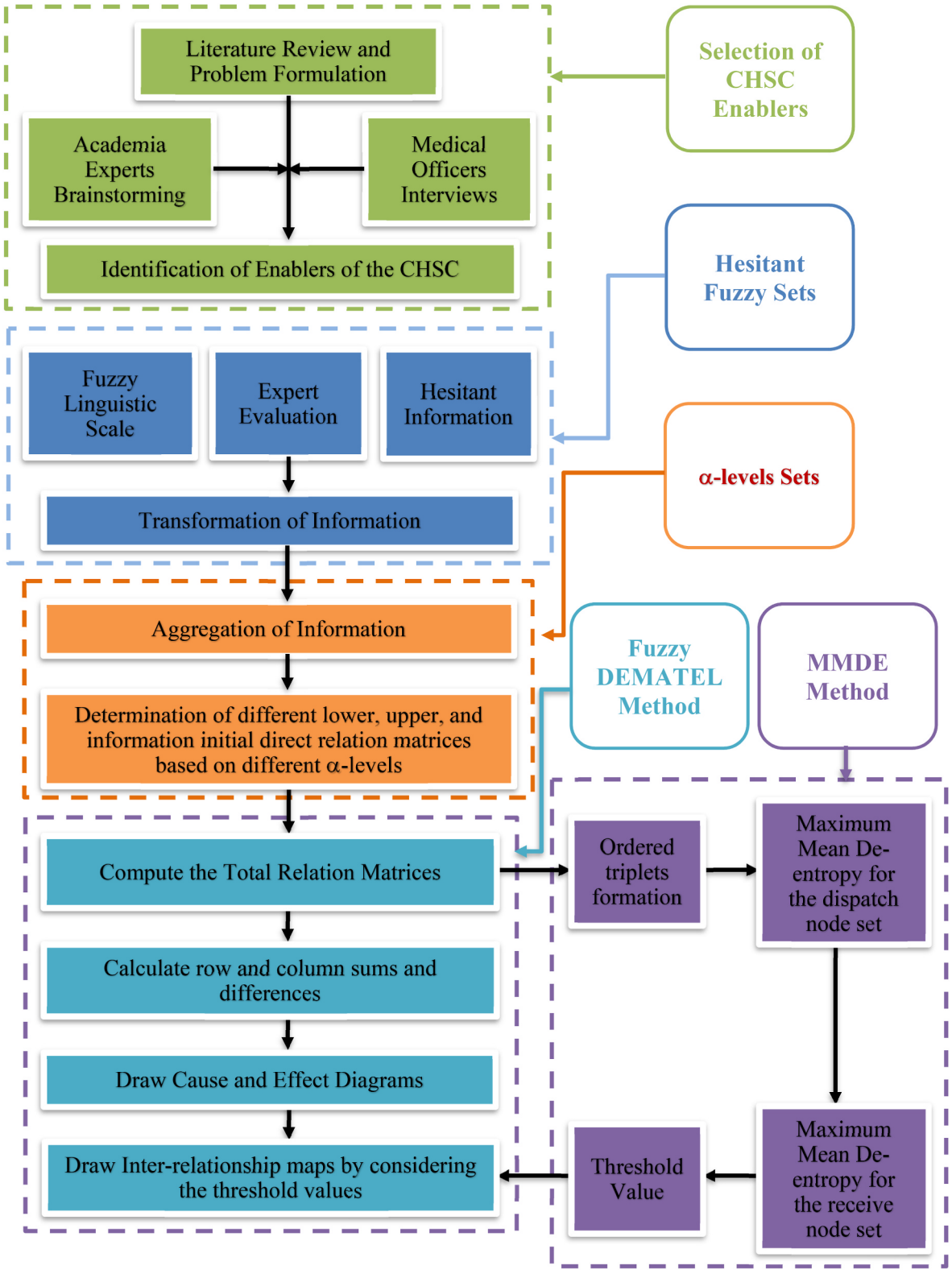


Fig. 1. Research methodology.

by five experts aggregated to get the information aggregation matrix denoted (see supplementary material for further information)

$$a_{ij} = min\left\{a_{ij}^{m}\right\}\ b_{ij} = \frac{1}{M}\sum_{m=1}^{M} b_{ij}^{m}\ c_{ij} = \frac{1}{M}\sum_{m=1}^{M} c_{ij}^{m}\ d_{ij} = max\left\{d_{ij}^{m}\right\}$$

Where m = 1, 2, …, M; $i,j = 1,2,\ldots,K$. (2)

The Expert Opinion Information Aggregation Matrix is given in Appendix 5.

Step IV Determination of lower bound matrix $\widehat{X}_{\alpha}^{L}$, upper bound matrix $\widehat{X}_{\alpha}^{U}$ and information matrix $\widehat{X}_{\alpha}^{Z}$

Table 4
Fuzzy linguistic terms and associated fuzzy numbers.

Linguistic Terms	Triangular Fuzzy Numbers
Extremely low influence (ELI)	(0, 0, 0.17)
Very low influence (VLI)	(0, 0.17, 0.33)
Low influence (LI)	(0.17, 0.33, 0.50)
Medium Influence (MI)	(0.33, 0.50, 0.67)
High influence (HI)	(0.50, 0.67, 0.83)
Very high influence (VHI)	(0.67, 0.83, 1)
Extremely High influence (EHI)	(0.83, 1, 1)

After obtaining the expert opinion aggregation matrix, the lower, upper, and information matrices are determined.

4.1. Determination of the lower and upper bound matrix

The lower and upper bound matrix can be determined by using Definition 2. For more details, refer to (Wang, 2009).

Definition 2. Let P be a fuzzy set defined for discourse universe R, for $\alpha \in [0, 1]$, then the α- The level set of 'P_α' can be defined as given in equation (3)

$$P_\alpha = \{\mu_P(x) \geq \alpha\}$$

$$= [min\{\mu_P(x) \geq \alpha\}, max\{\mu_P(x) \geq \alpha\}]$$

$$= [(x)_\alpha^L, (x)_\alpha^U] \quad (3)$$

Where $\mu_P(x)$ is denoted as the membership function of P_α and X as the universe of discourse.

4.2. Determination of the information matrix

The information aggregation matrix $\widehat{X} = [\widehat{x}_{ij}]_{K\times K}$, where $\widehat{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$ and let alpha-level sets be made $\widehat{X}$ as $\widehat{X}_\alpha = \left[\widehat{x}_{ij}^\alpha\right]_{K\times K}$, where $\widehat{x}_{ij}^\alpha = \left[(\widehat{x}_{ij})_\alpha^L, (\widehat{x}_{ij})_\alpha^U\right]$. Now for interval values $\left[(\widehat{x}_{ij})_\alpha^L, (\widehat{x}_{ij})_\alpha^U\right]$

Let ρ be a random variable with uniform distribution; then pdf is given by equation (4)

$$\begin{cases} f(\rho) = \begin{cases} \dfrac{1}{(\widehat{x}_{ij})_\alpha^U - (\widehat{x}_{ij})_\alpha^L}, \left(\widehat{x}_{ij}\right)_\alpha^L \leq \rho \leq \left(\widehat{x}_{ij}\right)_\alpha^U \\ 0, elsewhere \end{cases} \end{cases} \quad (4)$$

Sum of all probabilities $= \int_{(\widehat{x}_{ij})_\alpha^L}^{(\widehat{x}_{ij})_\alpha^U} f(\rho)d\rho = 1$ and $f(\rho) \geq 0$ for all $\rho \in$

Table 5
Opinion by expert I.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1		At most VLI	HI	At least HI	b/w LI & MI	b/w ELI & VLI	b/w VLI & LI	VLI	VHI	EHI
C2	b/w MI & HI		At least MI	At least HI	b/w LI & MI	HI	b/w LI & MI	At least VHI	b/w HI & VHI	b/w VHI & EHI
C3	MI	At most VLI		b/w HI & VHI	b/w LI & MI	LI	b/w LI & HI	b/w VLI & LI	VHI	b/w LI & MI
C4	HI	VLI	MI		HI	ELI	HI	b/w LI & MI	MI	LI
C5	MI	VLI	b/w LI & MI	b/w MI & HI		VLI	b/w HI & VHI	ELI	ELI	b/w VLI & LI
C6	HI	VHI	VHI	b/w LI & MI	b/w HI & VHI		HI	b/w MI & HI	HI	b/w HI & VHI
C7	ELI	ELI	ELI	b/w VLI & LI	b/w VLI & LI	VLI		LI	MI	LI
C8	b/w MI & VHI	b/w ELI & VLI	b/w MI & HI	LI	LI	ELI	b/w ELI & VLI		b/w MI & HI	HI
C9	At least HI	ELI	HI	b/w MI & HI	LI	VLI	VLI	ELI		VLI
C10	b/w LI & MI	LI	HI	HI	b/w VLI & LI	VLI	MI	MI	b/w HI & VHI	

Table 6
Opinion transformation matrix of Expert I.

	C1	C2	C3	C4	C5
C1		(0,0,.03,.33)	(.5,.67,.67,.83)	(.5,.85,1,1)	(.17,.33,.5,.67)
C2	(.33,.5,.67,.83)		(.33,.65,1,1)	(.5,.85,1,1)	(.17,.33,.5,.67)
C3	(.33,.5,.5,.67)	(0,0,.03,.33)		(.5,.67,.83,1)	(.17,.33,.5,.67)
C4	(.5,.67,.67,.83)	(0,.17,.17,.33)	(.33,.5,.5,.67),		(.5,.67,.67,.83)
C5	(.33,.5,.5,.67)	(0,.17,.17,.33)	(.17,.33,.5,.67)	(.33,.5,.67,.83)	
C6	(.5,.67,.67,.83)	(.67,.83,.83,1)	(.67,.83,.83,1)	(.17,.33,.5,.67)	(.5,.67,.83,1)
C7	(0,0,0,.17)	(0,0,0,.17)	(0,0,0,.17)	(0,.17,.33,.5)	(0,.17,.33,.5)
C8	(.33,.64,.7,1)	(0,0,.17,.33)	(.33,.5,.67,.83)	(.17,.33,.33,.5)	(.17,.33,.33,.5)
C9	(.5,.85,1,1)	(0,0,0,.17)	(.5,.67,.67,.83)	(.33,.5,.67,.83)	(.17,.33,.33,.5)
C10	(.17,.33,.5,.67)	(.17,.33,.33,.5)	(.5,.67,.67,.83)	(.5,.67,.67,.83)	(0,.17,.33,.5)
	C6	**C7**	**C8**	**C9**	**C10**
C1	(0,0,.17,.33)	(0,.17,.33,.5)	(0,.17,.17,.33)	(.67,.83,.83,1)	(.83,1,1,1)
C2	(.5,.67,.67,.83)	(.17,.33,.5,.67)	(.67,.97,1,1)	(.5,.67,.83,1)	(.67,.83,1,1)
C3	(.17,.33,.33,.5)	(.17,.47,.53,.83)	(0,.17,.33,.5)	(.67,.83,.83,1),	(.17,.33,.5,.67)
C4	(0,0,0,.17)	(.5,.67,.67,.83)	(.17,.33,.5,.67)	(.33,.5,.5,.67)	(.17,.33,.33,.5)
C5	(0,.17,.17,.33)	(.5,.67,.83,1)	(0,0,0,.17)	(0,0,0,.17)	(0,.17,.33,.5
C6		(.5,.67,.67,.83)	(.33,.5,.67,.83)	(.5,.67,.67,.83)	(.5,.67,.83,1)
C7	(0,.17,.17,.33)		(.17,.33,.33,.5)	(.33,.5,.5,.67)	(.17,.33,.33,.5)
C8	(0,0,0,.17)	(0,0,.17,.33)		(.33,.5,.67,.83)	(.5,.67,.67,.83)
C9	(0,.17,.17,.33)	(0,.17,.17,.33)	(0,0,0,.17)		(0,.17,.17,.33)
C10	(0,.17,.17,.33)	(.33,.5,.5,.67)	(.33,.5,.5,.67)	(.5,.67,.83,1)	

$\left[\left(\widehat{x}_{ij}\right)_{\alpha}^{L}, \left(\widehat{x}_{ij}\right)_{\alpha}^{U}\right]$.

Now, the information matrix $\widehat{X}_{\alpha}^{Z} = \left[\left(\widehat{x_{ij}}\right)_{\alpha}^{Z}\right]_{K\times K}$ can be determined by using equation (5):

$$\left[\left(\widehat{x_{ij}}\right)_{\alpha}^{Z} = \int_{\left(\hat{x}_{ij}\right)_{\alpha}^{L}}^{\left(\hat{x}_{ij}\right)_{\alpha}^{U}} \rho f(\rho) d\rho, i, j = 1, 2, \ldots, K. \right. \tag{5}$$

So, matrix $\widehat{X}_{\alpha}$ have three components $\widehat{X}_{\alpha}^{L}, \widehat{X}_{\alpha}^{U}$ *and* $\widehat{X}_{\alpha}^{Z}$ (see supplementary material for further information) (Zhang et al., 2023).

In this study, eleven alpha levels, i.e., α = {0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1} are considered for analysis of enablers of CHSC.

The matrix $\widehat{X}_{\alpha}$, has three components $\widehat{X}_{\alpha}^{L}, \widehat{X}_{\alpha}^{U}$ *and* $\widehat{X}_{\alpha}^{Z}$ that were calculated using equations (3)–(5) and shown in Appendix 6.

Step V: Determination of total relation matrices lower bound, upper bound and information matrices.

The normalized matrix can be determined by using the following equation (6):

$$\underline{X}_{\alpha}^{L} = \frac{1}{max\, i \sum_{j=1}^{k} \left(\widehat{x}_{ij}\right)_{\alpha}^{L}} \widehat{X}_{\alpha}^{L}, \quad \underline{X}_{\alpha}^{U} = \frac{1}{max\, i \sum_{j=1}^{k} \left(\widehat{x}_{ij}\right)_{\alpha}^{U}} \widehat{X}_{\alpha}^{U}, \underline{X}_{\alpha}^{Z} = \frac{1}{max\, i \sum_{j=1}^{k} \left(\widehat{x}_{ij}\right)_{\alpha}^{Z}} \widehat{X}_{\alpha}^{Z} \tag{6}$$

The total relation matrix $T_{\alpha}^{L} = \left[\left(t_{ij}\right)_{\alpha}^{L}\right]_{K\times K}$, $T_{\alpha}^{U} = \left[\left(t_{ij}\right)_{\alpha}^{U}\right]_{K\times K}$, $T_{\alpha}^{Z} = \left[\left(t_{ij}\right)_{\alpha}^{Z}\right]_{K\times K}$ can be determined by the following equation (7):

$$T_{\alpha}^{L} = \underline{X}_{\alpha}^{L}\left(I - \underline{X}_{\alpha}^{L}\right)^{-1}, T_{\alpha}^{U} = \underline{X}_{\alpha}^{U}\left(I - \underline{X}_{\alpha}^{U}\right)^{-1}, T_{\alpha}^{Z} = \underline{X}_{\alpha}^{Z}\left(I - \underline{X}_{\alpha}^{Z}\right)^{-1} \tag{7}$$

The total relation matrix T_{α}^{L}, T_{α}^{U} and T_{α}^{Z} can be determined by equations (6) and (7), as shown in Appendix 7.

Step VI: Computation of the sum of rows and columns of the total relation matrix for individual α values.

The sum of rows and columns of the total relation matrix can be determined by equations (8) and (9) for all α values ranging from 0 to 1 and shown in Appendix 8. For α = 0.1, it is shown in Table 7.

For the sum of rows

$$\left(R_i\right)_{\alpha}^{L} = \sum_{j=1}^{K} \left(t_{ij}\right)_{\alpha}^{L}, \left(R_i\right)_{\alpha}^{U} = \sum_{j=1}^{K} \left(t_{ij}\right)_{\alpha}^{U}, \left(R_i\right)_{\alpha}^{Z} = \sum_{j=1}^{K} \left(t_{ij}\right)_{\alpha}^{Z} \tag{8}$$

And for the sum of columns

$$\left(C_j\right)_{\alpha}^{L} = \sum_{i=1}^{K} \left(t_{ij}\right)_{\alpha}^{L}, \left(C_j\right)_{\alpha}^{U} = \sum_{i=1}^{K} \left(t_{ij}\right)_{\alpha}^{U}, \left(C_j\right)_{\alpha}^{Z} = \sum_{i=1}^{K} \left(t_{ij}\right)_{\alpha}^{Z} \tag{9}$$

Step VII: Cause-effect diagram.

The cause-effect diagram takes the sum and difference of corresponding rows and columns to different alpha levels, enhancing the analysis by providing more choices.

The cause-effect diagram can also be made by taking the average of the sum and differences of corresponding rows and columns of all the alpha levels $0 \le \alpha_1 < \ldots < \alpha_P \le 1$ by using equations (10) and (11) as shown in Table 8:

$$\underline{R}_i^{L} = \frac{1}{P}\sum_{p=1}^{P}\left(R_i\right)_{\alpha_p}^{L}, i = 1, 2, \ldots, K, \underline{R}_i^{U} = \frac{1}{P}\sum_{p=1}^{P}\left(R_i\right)_{\alpha_p}^{U}, i = 1, 2, \ldots, K$$

$$\underline{R}_i^{Z} = \frac{1}{P}\sum_{p=1}^{P}\left(R_i\right)_{\alpha_p}^{Z}, i = 1, 2, \ldots, K \tag{10}$$

$$\underline{C}_j^{L} = \frac{1}{P}\sum_{p=1}^{P}\left(C_j\right)_{\alpha_p}^{L}, j = 1, 2, \ldots, K, \underline{C}_j^{U} = \frac{1}{P}\sum_{p=1}^{P}\left(C_j\right)_{\alpha_p}^{U}, j = 1, 2, \ldots, K$$

$$\underline{C}_j^{Z} = \frac{1}{P}\sum_{p=1}^{P}\left(C_j\right)_{\alpha_p}^{Z}, j = 1, 2, \ldots, K \tag{11}$$

The cause-and-effect diagram is drawn by taking Ri + Cj on the x-axis and Ri - Cj on the y-axis. The cause-and-effect diagram was drawn for α = 0.1 and α_{mean}, as shown in Figs. 2 and 3, respectively, for the lower, upper and information matrices. The MMDE method (Steps VIII to XI) is now followed to find the threshold value, as discussed in Appendix 9.

Step XII: Inter-relationship Map of Enablers

The MMDE method is applied to find the threshold value by considering the case of α_{mean} to check the criticality of identified enablers and their interrelationship. The critical values (those with higher values than the threshold value) are considered from the total relation matrices for drawing the interrelationship maps. The inter-relationship map is drawn for lower, information, and upper matrices by considering their respective threshold values shown in Figs. 11 and 12, and 13, respectively.

5. Result and discussion

In the present study, an α-level based hesitant fuzzy DEMATEL with MMDE was employed to identify the most substantial enabler and their interrelationship for implementing CE principles in HCSC. The result from the fuzzy DEMATEL method helps find the strength of the correlation between enablers by using Ri + Cj values and categorizing enablers in the causal and effect group using Ri – Cj values. By giving importance to causal group enablers, effect group enablers can be improved, ultimately easing the implementation of CE in the Indian HSC.

5.1. Correlation between the enablers

The higher Ri + Cj values identify the more substantial contribution of the enabler in implementing CHSC. The identified enablers were

Table 7
The sum of rows and columns of the total relation matrix for α = 0.1

	Lower				Upper				Information			
	Ri + Cj	Rank	Ri - Cj	Cause/Effect	Ri + Cj	Rank	Ri - Cj	Cause/Effect	Ri + Cj	Rank	Ri - Cj	Cause/Effect
C1	1.133	5	−0.207	Effect	12.096	3	−1.166	Effect	5.075	5	−0.561	Effect
C2	1.121	6	0.740	Cause	10.352	10	2.719	Cause	4.448	8	1.457	Cause
C3	1.551	4	−0.611	Effect	11.496	5	−0.551	Effect	5.119	4	−0.588	Effect
C4	1.103	7	−0.267	Effect	12.321	2	−0.317	Effect	5.145	3	−0.239	Effect
C5	0.683	9	−0.255	Effect	10.689	8	−0.396	Effect	4.282	9	−0.321	Effect
C6	1.616	2	1.483	Cause	10.944	7	2.262	Cause	4.965	6	1.742	Cause
C7	0.629	10	−0.462	Effect	10.604	9	−2.331	Effect	4.223	10	−1.170	Effect
C8	0.907	8	0.079	Cause	11.400	6	0.447	Cause	4.702	7	0.212	Cause
C9	1.671	1	−0.684	Effect	11.980	4	−0.584	Effect	5.379	2	−0.620	Effect
C10	1.589	3	0.185	Cause	12.407	1	−0.083	Effect	5.503	1	0.089	Cause

Table 8
The sum of rows and columns of the total relation matrix for α_{mean}.

	Lower				Upper				Information			
	Ri + Cj	Rank	Ri - Cj	Cause/Effect	Ri + Cj	Rank	Ri - Cj	Cause/Effect	Ri + Cj	Rank	Ri - Cj	Cause/Effect
C1	2.098	5	−0.400	Effect	7.798	3	−0.921	Effect	4.325	3	−0.608	Effect
C2	1.716	7	1.038	Cause	6.487	10	2.155	Cause	3.582	8	1.483	Cause
C3	2.254	3	−0.561	Effect	7.449	5	−0.534	Effect	4.282	5	−0.550	Effect
C4	2.015	6	−0.280	Effect	7.908	2	−0.326	Effect	4.324	4	−0.279	Effect
C5	1.389	10	−0.287	Effect	6.593	8	−0.440	Effect	3.423	10	−0.359	Effect
C6	2.215	4	1.612	Cause	7.006	7	2.064	Cause	4.081	6	1.783	Cause
C7	1.424	9	−0.653	Effect	6.577	9	−1.656	Effect	3.437	9	−1.062	Effect
C8	1.714	8	0.171	Cause	7.167	6	0.379	Cause	3.854	7	0.253	Cause
C9	2.373	2	−0.711	Effect	7.687	4	−0.662	Effect	4.447	2	−0.679	Effect
C10	2.437	1	0.071	Cause	8.046	1	−0.060	Effect	4.638	1	0.020	Cause

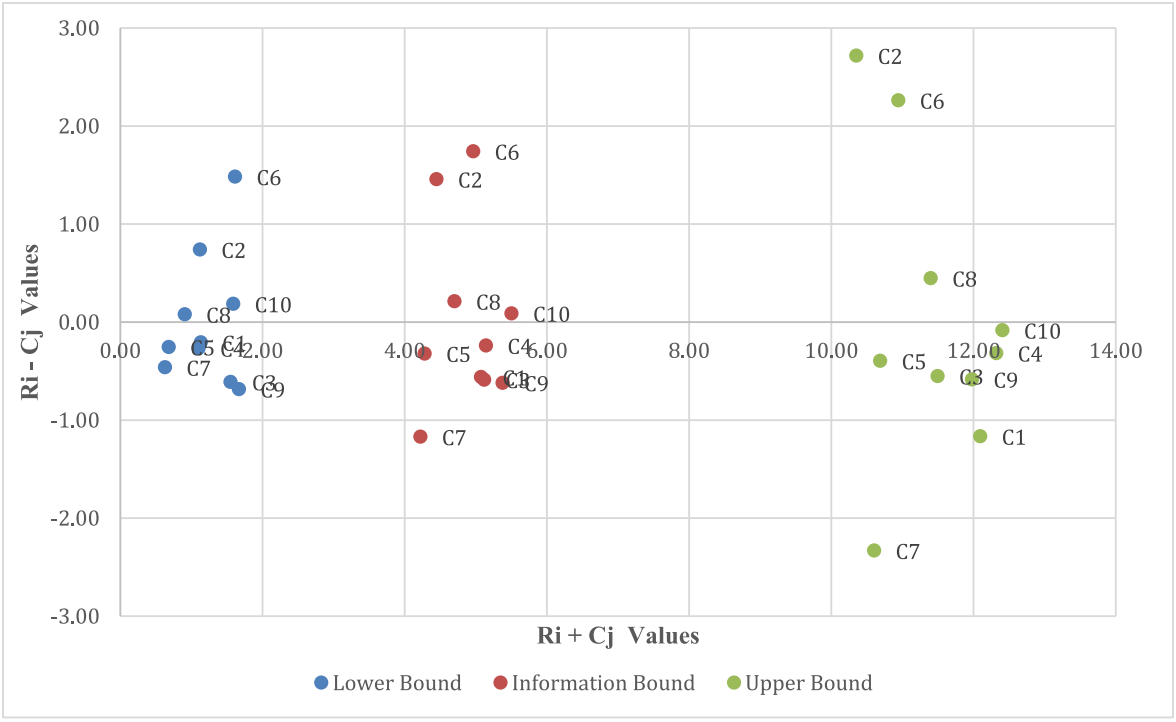


Fig. 2. Cause and effect diagram for α = 0.1.

ranked according to their Ri + Cj values, as in Tables 7 and 8, for α = 0.1 and $\alpha_{mean,}$ respectively. The obtained rankings were further examined by changing the alpha values for lower, upper, and information matrices as per Figs. 4–6, respectively, to determine any personal bias in experts' opinions. There was no significant deviation in ranking by changing the values of alpha. Long-term strategic planning for circularity (C10) correlates with other enablers, while the incentive scheme for product return (C5) is the least correlated with other enablers. The correlation strength of long-term strategic planning for circularity is supported by the enablers influencing C1, C3, C4, C7, and C9, whereas they are affected by C2, C6, and C8, as shown in Figs. 10–12. Long-term strategic planning for circularity can work as a catalyst for other factors that can be used to implement CE in healthcare industries. The legislation, government policies, and top-level management influence long-term strategic planning. The planning should be based on long-term sustainable goals rather than sticking to short-term financial objectives (Patel et al., 2021).

Revamping packaging and procurement practices to encourage recycling (C9) is the next factor having the highest correlation strength influencing extended producer responsibility (C1) and applicability of corporate social responsibility (C7) and affected by Pressure from favorable national policies for the medical device sectors (C2) and pressure enforced by stakeholders for international agreements (C6). Effective packaging design techniques and reusing packaging materials can lower carbon emissions and promote circularity (Kalmykova et al., 2018; Baddley and Rasheed, 2023). The incentive scheme for product return back (C5) is the least correlated with other enablers. As per Fig. 12, C5 is affected by pressure enforced by stakeholders for international agreements (C6). Due to medical device safety, quality and hygiene issues, the incentive scheme for product return is less prominent among other enablers. (Mura et al., 2020).

5.2. Causal group

Higher Ri – Cj values indicate the strong impact of enablers on implementing CE in HCSC. By observing positive Ri – Cj values (from Tables 7 and 8), in the causal group, there were four enablers: pressure enforced by stakeholders for international agreements (C6), favorable national policies for the medical device sectors (C2), transfer of technology and knowledge management (C8) and long-term strategic planning for circularity (C10). The ranking was obtained as C6 > C2 > C8 > C10. The obtained rankings were further examined by changing the alpha values for lower, upper, and information matrices as per Figs. 7–9, respectively, to determine any personal bias in experts' opinions. No

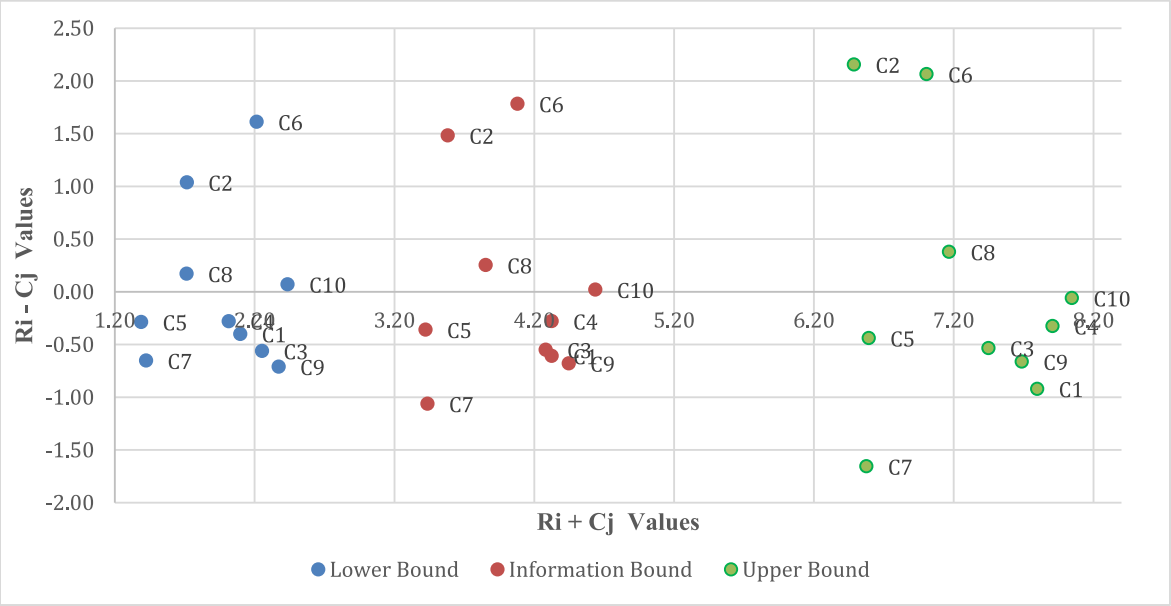


Fig. 3. Cause and effect diagram for α_{mean}.

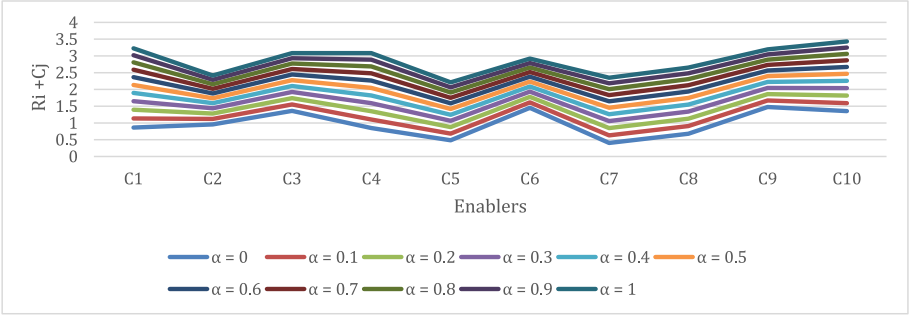


Fig. 4. Ri + Cj values for lower bound Matrix at the different alpha level.

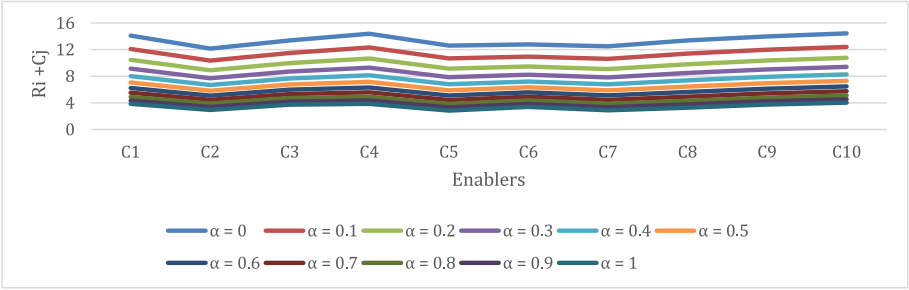


Fig. 5. Ri + Cj values for upper bound Matrix at the different alpha level.

significant deviation in ranking further confirms that no expert was heavily biased. It is also observed from the interrelationship map (Figs. 10–12) that causal group enablers were found in the bottom line, affecting the other enablers. So now, it can be clearly said that pressure enforced by stakeholders for international agreements (C6) is a predominant enabler, which was also found necessary in the past study done in various industries (Dohale et al., 2023; Hina et al., 2022; Lahane et al., 2021a; Moktadir et al., 2018). To sustain itself in the global market, all the norms and regulations must be followed, which can enhance business competitiveness with a green image. Favorable national policies for the medical device sectors (C2) are the next impactful enabler of CHSC, which is supported by various new policies initiated by the Indian government such as make in India, startup India, digital Bharat, Aatmanirbhar Bharat, National Logistics Policy (NLP), National Master Plan (NMP), production linked scheme and scheme for promotion of medical devices parks. Transfer of technology and knowledge management (C8) also correlates with one of the studies on developing sustainable healthcare systems in developing countries (Karamat et al., 2019).

5.3. *Effect group*

Effect group enablers are directly affected by causal enablers, which eases the CHSC implementation process. By observing negative Ri – Cj

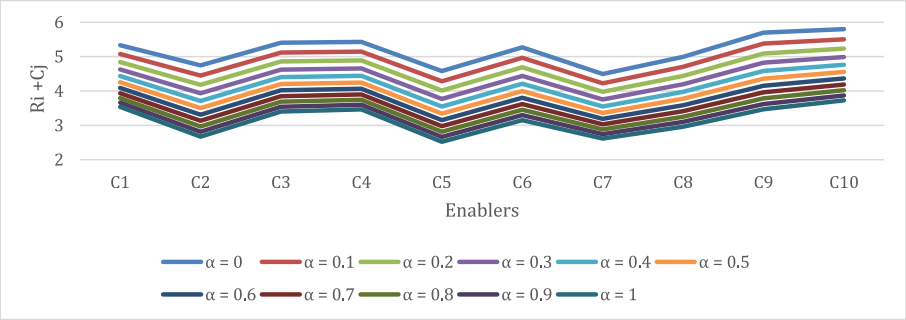


Fig. 6. Ri + Cj values for Information Matrix at the different alpha level.

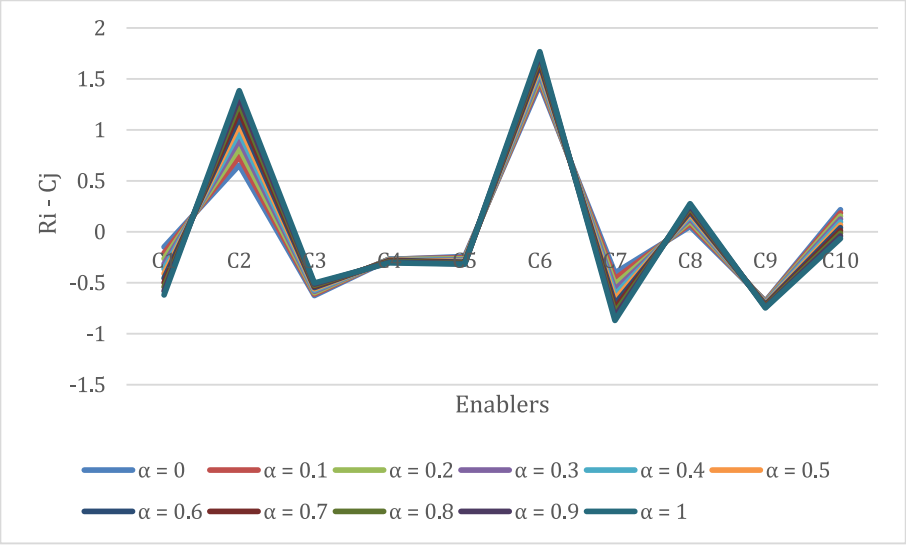


Fig. 7. Ri - Cj values for lower bound Matrix at the different alpha levels.

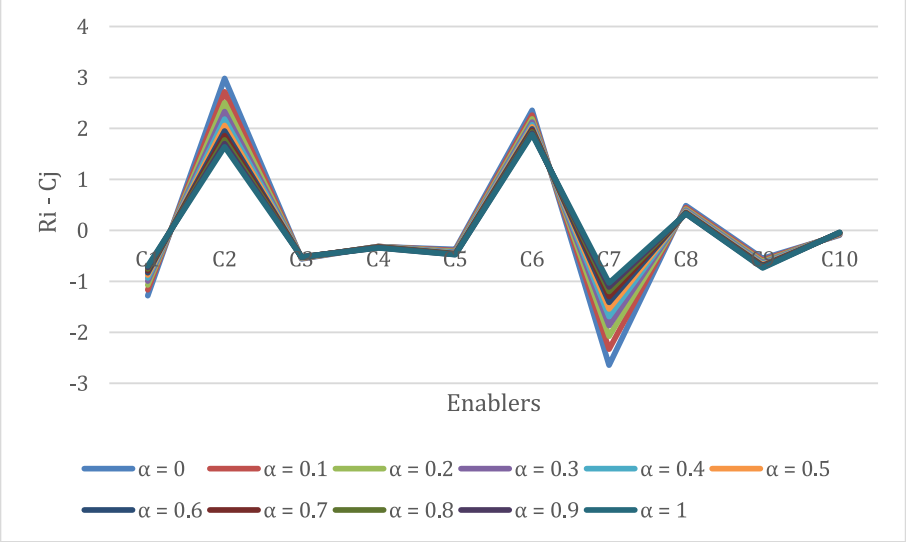


Fig. 8. Ri - Cj values for upper bound Matrix at the different alpha levels.

values (from Tables 7 and 8), in the causal group, there were six enablers: extended producer responsibility (C1), adoption of the 6R concept to boost the economy over time (C3), market share gain and competitiveness (C4), incentive scheme for product return back (C5), applicability of corporate social responsibility (C7) and revamping packaging and procurement practices to encourage recycling (C9). The ranking was obtained as C7 > C9 > C1 > C3 > C5 > C4, arranged by the descending order of absolute values of Ri – Cj, with no significant deviation observed while changing the alpha values as per Figs. 8–10. Corporate social responsibility (C7) has the highest effect among other

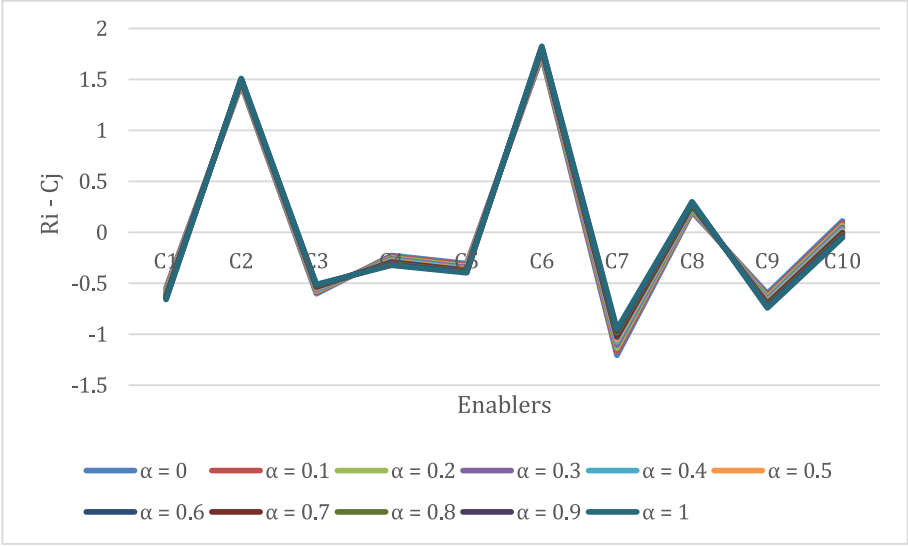


Fig. 9. Ri - Cj values for information Matrix at the different alpha levels.

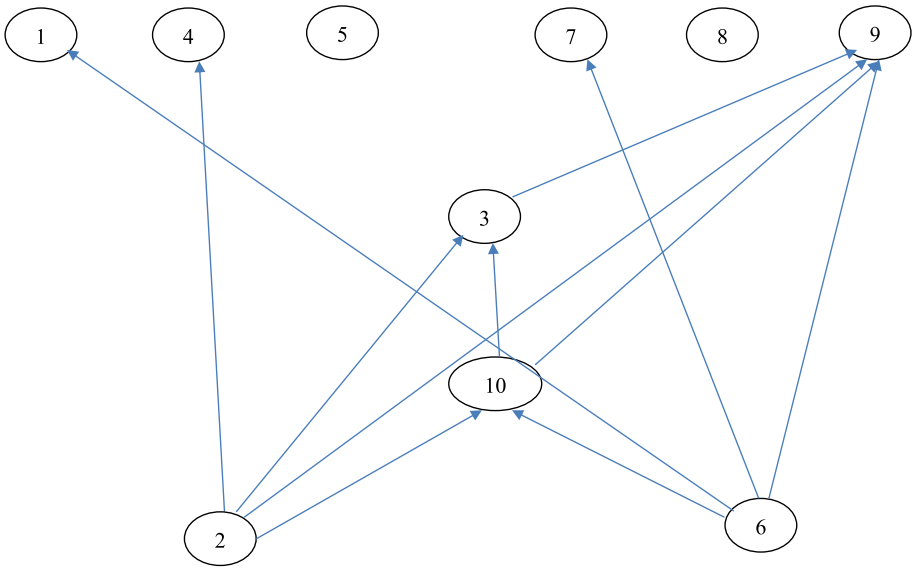


Fig. 10. Interrelationship map of enablers for lower matrix.

enablers. Corporations should understand their responsibility towards internal and external stakeholders while keeping high ethical standards when implementing CE. The second affected enabler is revamping packaging and procurement practices to encourage recycling (C9), which was also the second highly correlated enabler, confirming the criticality of this enabler to attain CHSC. Due to high initial investment, industries are reluctant to adopt CE, making market share gain and competitiveness (C4) a less affected enabler.

6. Research implications

Theoretical Implications.

Most existing studies have focused on identifying enablers in the HSC (Hossain and Thakur, 2024; Macneill et al., 2020). However, no published research considers the CE in the Indian HSC. To fill this research gap, this study identifies the enablers of a CHSC through a comprehensive analysis of cause and effect, interrelationships, and priorities for Indian industries. The theoretical contribution can be summarized into the following points.

1) The study narrows the extensive literature into ten critical enablers, identified by a thorough literature review and expert inputs.
2) Among these critical enablers, the most prominent enabler was identified.
3) The research proposed the first of its kind to use alpha level sets based on an integrated fuzzy DEMATEL-MMDE approach with hesitant information for finding interrelationships amongst each enabler.
4) The proposed method provides new dimensions for analyzing enablers by taking the concept of alpha-level sets. Each enabler's effect on the other was also quantified and represented in tabular and graphical form. The MMDE method finds the threshold value, confirming the most critical enabler by drawing interrelationship maps.

Policy Suggestions.

The policy suggestions are based on the discussion provided in section 4, the opinions made by experts and the CHSC status in India.

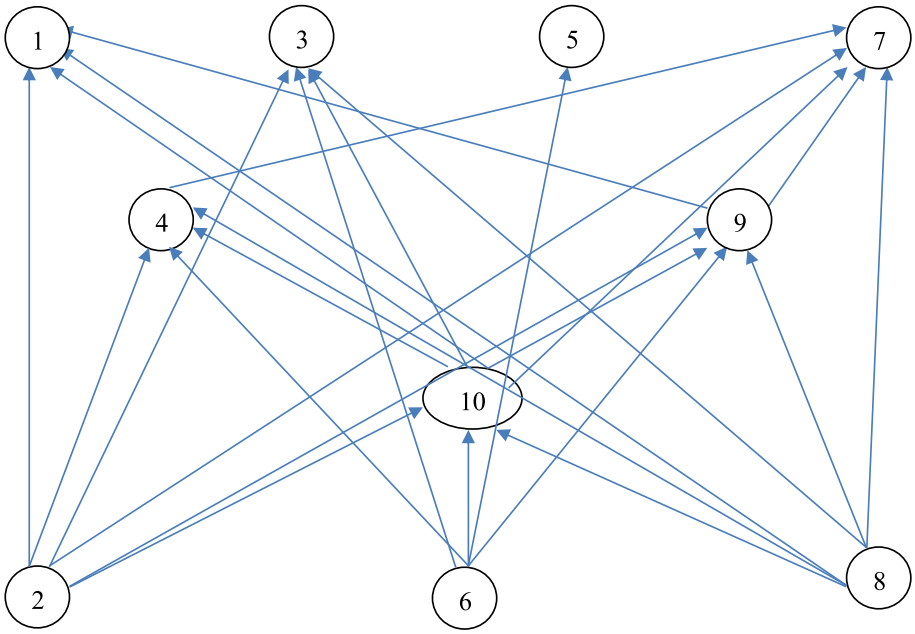


Fig. 11. Interrelationship map of enablers for upper matrix.

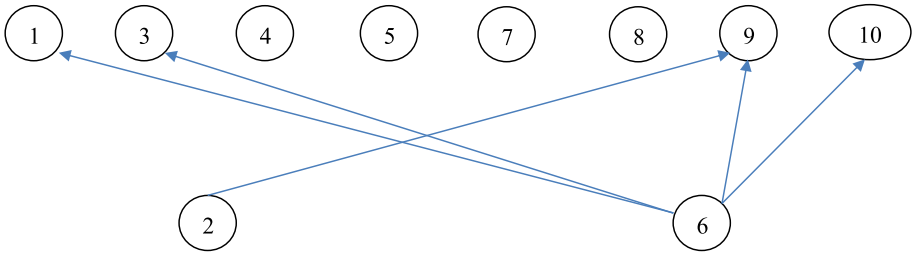


Fig. 12. Interrelationship map of enablers for information matrix.

1) The developed model indicates that stakeholder pressure for international agreements is a primary enabler in the causal category, emphasizing the need for CE implementation to sustain the global market (Dixit and Dutta, 2024; Upadhyay and Shukla, 2024). To accomplish this, production managers should know the products' recycling/reuse potential and carbon footprint and implement them in design thinking (Karloopia and Agrawal, 2024; Suleman et al., 2023).
2) HSC requires long-term strategic planning for circularity since healthcare systems utilize many resources and generate a lot of waste, including dangerous materials. Instead of concentrating only on the immediate financial gains, managers should develop long-term planning for circularity, considering the long-term ecological, economic, and social benefits of implementing a circular supply chain. Potential conflicts can be avoided by including all internal and external stakeholders in strategic planning (Khan et al., 2022). Planning should consider globalization and environmental regulations to support the company's objectives for sustainable future growth. Top management's engagement can give the company a competitive edge by accelerating the implementation of strategic planning and investments to attain circularity (Kayikci et al., 2022a,b).
3) Examine the goals and methods of Extended Producer Responsibility (EPR) programs to maximize the potential for circularity (Wang et al., 2023). The producer's responsibility can be extended by incorporating extended warranty and right-to-repair schemes. Materials created by producers are collected, processed, and recycled at their own expense. To support resource life extension, policymakers should create rules and regulations for EPR in the healthcare sector.
4) The Indian government has initiated the National Medical Device Policy 2023, which includes a comprehensive framework based on coordinated strategies for sustainable development and growth of the healthcare sector economic support for achieving a 10–12% share in the global market over the next 25 years (Karloopia and Agrawal, 2024). The study also suggests that the enabler, favorable national policies for the medical device sectors (C2), is the second enabler in the causal category. The Indian government needs to take the CE as a necessary tool to include in this policy to foster the CHSC.
5) By implementing circular practices, healthcare companies can improve their green image and market share, obtain a competitive advantage, and establish a favorable reputation among eco-aware consumers (Dziedzic et al., 2022).
6) The manufacturers should encourage the intensive scheme for product return so that medical devices like orthopedic belts, implants, etc., can be reused by other patients, further strengthening the CE. Medical equipment disposal safety is another issue that can be addressed with a program that offers incentives for product returns (Mura et al., 2020). More CE can be fostered via incentive programs that reduce the excessive usage of single-use medical devices. In order to achieve zero waste and reduce environmental degradation, deposit refund systems offer customers an incentive scheme whereby they pay at the time of purchase and receive reimbursement when they return the obsolete medical devices to the authorized recycler or

manufacturer (Sharma et al., 2020). Most of product are not returning back due to lack of the logistics of return system. The use of digital technologies can certainly provide the edge in managing product return system. To encourage this, the Indian government should provide subsidies to the manufacture for using digital technologies in terms of tax rebate or by giving financial aids.

7) The medical device sector can significantly reduce environmental emissions and resources by incorporating the 6R concept to strengthen the CE (Hoveling et al., 2024). The healthcare devices industries should implement the following measures
   - Introducing devices at a reasonable cost that make it undesirable to use other, less eco-friendly gadgets (refuse).
   - Allowing users to share their devices or providing several features on a single device (rethink).
   - Additive manufacturing technology can be used for cutting back on energy and material usage by using (reduce) (Kumar and Chhabra, 2022).
   - Reusing medical devices for several cycles of usage (reuse) following decontamination.
   - Creating devices that can be remanufactured when their useful lives are ending.
   - Recycle the expensive part of the product into new products.
8) The enabler "revamping packaging and procurement practices to encourage recycling" suggests that while selecting suppliers, priority should be given to those who practice or are willing to implement CE principles. This approach ensures that suppliers align with the company's sustainability goals and contribute to a CE. Circularity can be accelerated by educating stakeholders about using recyclable or biodegradable packaging as an alternative to plastic (Gue et al., 2020). Effective packaging design techniques and reusing packaging materials can lower carbon emissions and promote circularity (Kalmykova et al., 2018; Baddley and Rasheed, 2023).
9) Organizations may promote a CE, draw in new potential clients, and maintain long-term viability without sacrificing quality through strategic CSR. For this, the industries should conduct business ethically and continuously work for the welfare of their external stakeholders—customers, society, and the environment—as well as their internal stakeholders, which include management and staff (Aheleroff et al., 2021; Daú et al., 2019).
10) In the digital era, the transfer of technology and knowledge can foster a CE by using digital technology to track and trace the product. The government, healthcare industries, and academia should take the initiative to run various training programs, seminars, and conferences to raise awareness about the use of digital technology and how to strengthen the CE (Vishwakarma et al., 2023; Kamble et al., 2023). Hospitals can use mobile health (mHealth) to provide better communications between patients and healthcare providers, especially those living in remote locations, in less time and cost, which can help achieve good health and well-being (SDG-3) (Swain et al., 2024).

7. Conclusion and future scope

The healthcare industry faces significant challenges in implementing CE (CE) practices due to their complexity, safety, and hygiene concerns. A robust healthcare system requires strong supply chains that can save lives efficiently and cost-effectively. The transition in economies and evolving disease patterns necessitate increasing resources in the healthcare sector by reusing them. Despite the global pressure from increasing demand and various natural and artificial disasters, there is an urgent need to implement CE in the healthcare sector. CE practices are crucial for the optimal utilization of resources throughout their lifecycle and beyond. The Indian government have recently initiated various amendments in healthcare device policies to become self-reliant in the healthcare sectors, which motivated us to analyze the enablers of CHSC. This research was conducted to find critical enablers for implementing CE in the Indian healthcare industries.

This research identified ten enablers through an extensive literature review and brainstorming sessions with medical officers and academic experts. The importance and interrelationships of enablers were performed using the alpha-level sets based on the fuzzy DEMATEL method, incorporating hesitant information from five experts. The MMDE method determines the threshold value, which helps identify the critical relationships between causes and effects.

Long-term strategic planning for circularity (C10) has the highest correlation with other enablers, which was also a causal enabler, indicating the criticality of the involvement of policymakers and top management to frame clear and consistent guideline with the help of researchers and industry experts, to follow in the long run to foster the CE in healthcare. Corporate Social Responsibility (CSR) emerges as the most effective enabler, emphasizing the responsibility of corporations towards the well-being of their internal and external customers. The top enabler in the causal category is stakeholder pressure for international agreements, highlighting stakeholders' vigilance for sustainability. The study concludes that the stakeholders' role is critical in effectively implementing CE practices in the healthcare sector—all the stakeholders aid in CE implementation by adhering to 6R concepts to use resources efficiently.

The study also presents theoretical implications and policy suggestions to policymakers, researchers, and industrial practitioners to implement CE in their industry's supply chain. The presented framework can be used to improve the organization's circular performance and build a green image. With the help of alpha-level sets, it was also found that there was no significant bias in the results.

Limitations and Future Research.

While this study focuses on India, its findings can be helpful for other developing countries. Future research could include more experts from different countries to generalize the results. In this study, to enhance the CWW decision-making process, the HFLTS was introduced, which represents the set of consecutive linguistic term sets. In the real world, it is possible that if the decision is made by different groups of experts (from various specializations, industries or other geographical locations), then their opinion may not be in the set of consecutive linguistic terms (referred to as rough HFLTS or extended hesitant fuzzy linguistic term set (EHFLTS)) can also be taken into consideration for future research.

Other techniques like fuzzy AHP, fuzzy ANP, fuzzy BWM, fuzzy TOPSIS, TISM, and fuzzy FUCOM could be applied to prioritize enablers and compare results. Although this study used the MMDE method to calculate the threshold value, methods like CIS or Lenth's could also be explored. The present research focuses on finding CE enablers in the Indian HSC industries. It can be extended to other industries like automobiles, construction, textiles, food processing, etc.

CRediT authorship contribution statement

Deepak Agrawal: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sumit Gupta:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chandni Dusad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.L. Meena:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G.S. Dangayach:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sandeep Jagtap:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition.

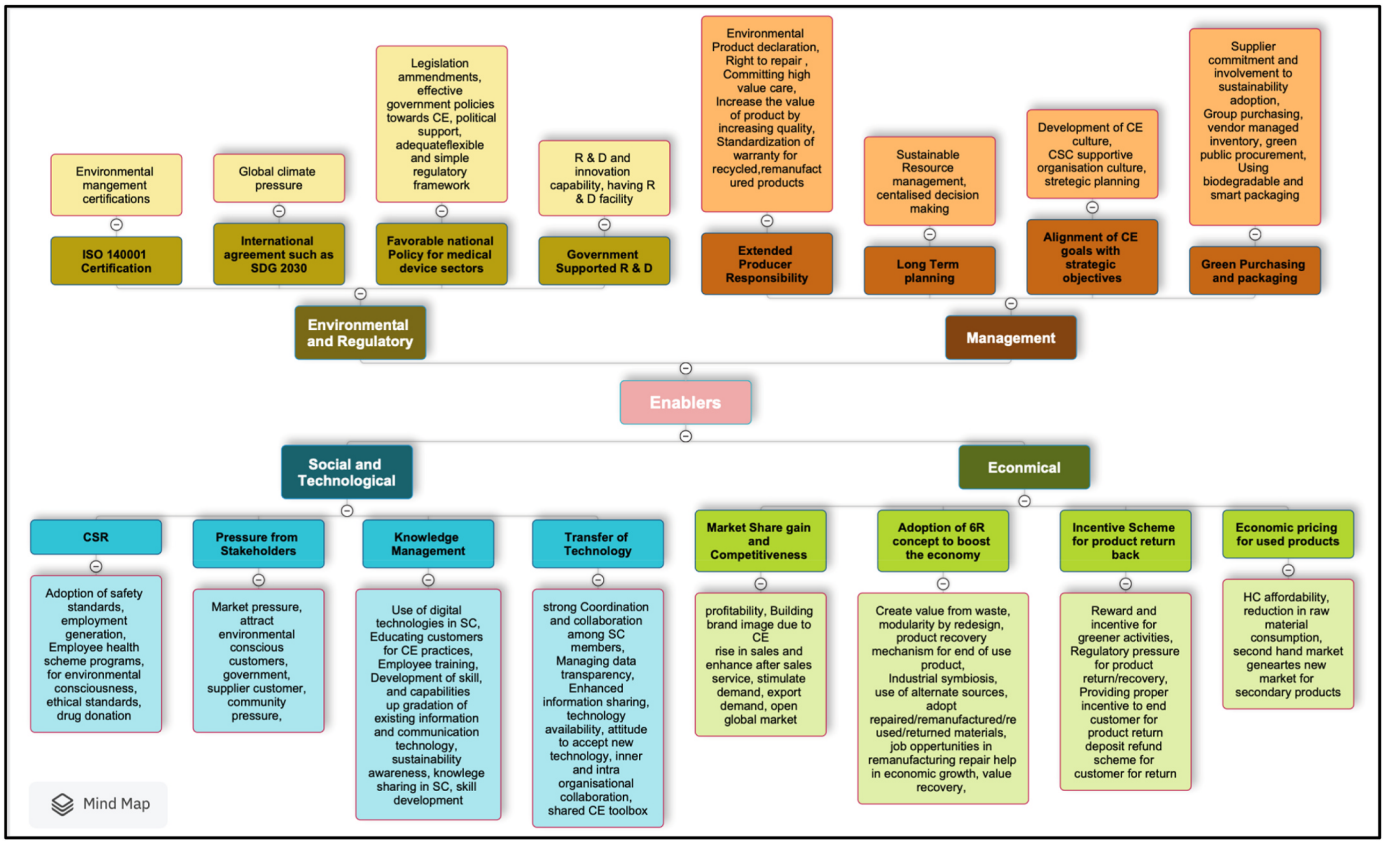
Declaration of competing interest

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

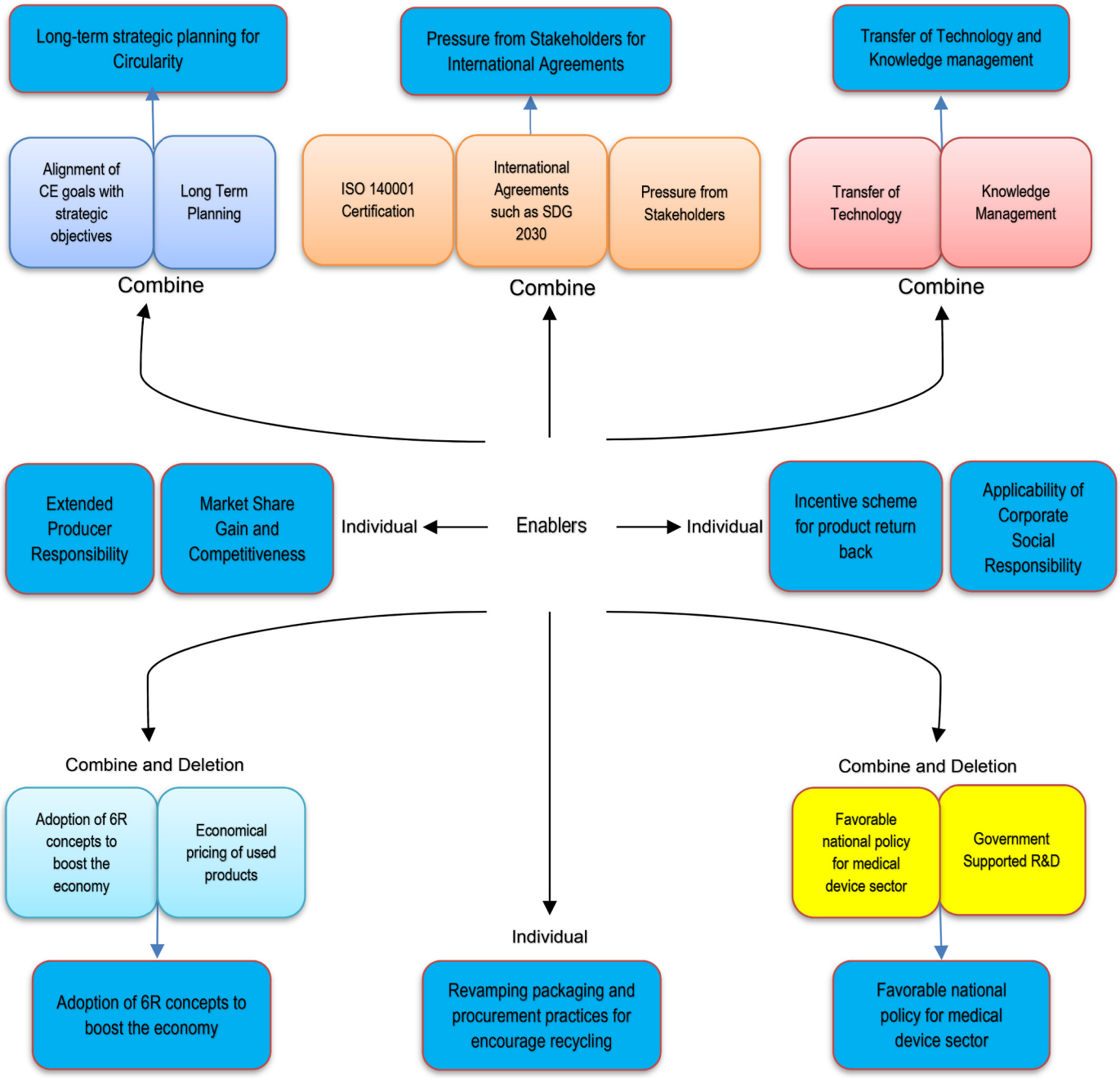
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2025.100882.

Appendices



Appendix 1: Mind Map of CHSC Enablers (Initial Screening by Group Brainstorming)



Appendix 2: Enablers Screening and Finalization

Appendix 3. Expert opinion about the enablers of Experts II, III, IV and V

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1		ELI, At most VLI, ELI, ELI	VHI, b/w MI & HI, LI, MI	VHI, b/w MI & HI, At most LI, At most LI	b/w MI & HI, HI, MI, MI	ELI, At most VLI, b/w VLI & LI, At most VLI	b/w MI & HI, VHI, HI, b/w MI & HI	At most MI, At most LI, LI, MI	At least VHI, HI, MI, MI	b/w VHI & EHI, b/w LI & MI, HI, HI
C2	At least MI, b/w MI & VHI, HI, At most LI		b/w MI & HI, b/w MI & VHI, b/w MI & HI, b/w MI & HI	VHI, HI, HI, HI	MI, b/w VLI & MI, MI, b/w MI & HI	LI, LI, At most LI, ELI	b/w MI & HI, b/w HI & VHI, At most MI, MI	At least EHI, At least MI, HI, b/w LI & MI	At least VHI, At least HI, HI, b/w MI & HI	VHI, VHI, HI, HI

(*continued on next page*)

(*continued*)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C3	b/w VLI & LI, b/w MI & HI, b/w HI & EHI, b/w MI & HI	ELI, At most VLI, ELI, ELI		At least VHI, b/w MI & VHI, b/w LI & HI, b/w HI & VHI	b/w MI & HI, At most MI, HI, b/w MI & HI	ELI, At most VLI, At most VLI, ELI	At least MI, LI, MI, VLI	b/w VLI & LI, b/w LI & MI, At most VLI, VLI	b/w VHI & EHI, At least VHI, VHI, HI	b/w HI & VHI, b/w MI & HI, MI, HI
C4	b/w MI & HI, At least MI, At most LI, HI	ELI, At least MI, At most VLI, LI	b/w MI & HI, HI, b/w MI & HI, b/w LI & HI		VHI, HI, b/w HI & VHI, HI	b/w HI & VHI, b/w MI & HI, At most LI, b/w MI & HI	b/w MI & HI, At least MI, MI, LI	b/w VLI & MI, b/w LI & HI, At most MI, b/w MI & HI	b/w LI & MI, MI, At most LI, MI	At most LI, MI, LI, LI
C5	b/w MI & HI, b/w LI & HI, HI, VHI	ELI, At most VLI, ELI, ELI	b/w MI & HI, MI, At most LI, MI	b/w HI & VHI, b/w LI & HI, LI, At most MI		ELI, VLI, At most VLI, ELI	b/w LI & MI, MI, LI, b/w MI & HI	ELI, VLI, LI, ELI	b/w VLI & LI, At least VHI, VLI, ELI	b/w LI & MI, b/w HI & VHI, VLI, LI
C6	b/w HI & EHI, VHI, VHI, b/w HI & VHI	At least VHI, b/w HI & EHI, HI, VHI	EHI, At least HI, VHI, EHI	At most LI, b/w VLI & LI, At most LI, LI	b/w HI & VHI, b/w LI & HI, At least MI, VHI		VHI, MI, HI, HI	At least HI, MI, At least VHI, b/w MI & VHI	VHI, At least HI, At least VHI, VHI	At least VHI, At least VHI, b/w HI & VHI, At least VHI
C7	b/w MI & HI, MI, HI, MI	ELI, ELI, ELI, ELI	b/w ELI & VLI, At most VLI, At most VLI, At most VLI	b/w LI & MI, At most LI, b/w MI & HI, b/w MI & HI	b/w VLI & MI, At most VLI, At most LI, HI	ELI, VLI, ELI, VLI		b/w LI & MI, At most VLI, b/w LI & MI, HI	MI, b/w VLI & LI, ELI, LI	MI, ELI, ELI, MI
C8	At least HI, ELI, b/w HI & VHI, b/w MI & HI	b/w VLI & LI, VLI, b/w ELI & VLI, HI	HI, b/w MI & HI, b/w MI & VHI, b/w HI & VHI	MI, At most MI, MI, HI	b/w ELI & VLI, ELI, At most LI, At most VLI	b/w LI & HI, b/w LI & MI, b/w MI & HI, MI	VLI, VLI, HI, LI		At least HI, b/w MI & HI, b/w MI & VHI, HI	EHI, HI, At least HI, b/w LI & HI
C9	At least VHI, b/w MI & HI, HI, HI	b/w ELI & VLI, VLI, ELI, ELI	b/w MI & VHI, b/w MI & HI, At least HI, b/w MI & HI	b/w HI & VHI, HI, MI, HI	MI, At most LI, ELI, At most LI	ELI, b/w MI & HI, At most VLI, ELI	At least MI, b/w MI & HI, VLI, HI	ELI, LI, ELI, HI		MI, At most MI, At least HI, b/w MI & HI
C10	b/w LI & HI, At least HI, HI, VHI	ELI, b/w VLI & LI, VLI, HI	At least HI, b/w HI & VHI, HI, VHI	At least HI, b/w LI & MI, At least HI, HI	At most MI, At most LI, b/w MI & HI, b/w MI & HI	ELI, VLI, MI, At most VLI	b/w MI & HI, MI, b/w MI & HI, HI	At least HI, MI, HI, HI	b/w HI & EHI, At least HI, b/w HI & VHI, b/w HI & VHI	

Appendix 4. Opinion transformation matrix of Experts II, III, IV and V

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1		(0,0,0,.17), (0,0,.03,.33), (0,0,0,.17), (0,0,0,.17)	(.67,.83,.83,1), (.33,.5,.67,.83), (.17,.33,.33,.5), (.33,.5,.5,.67)	(.67,.83,.83,1), (.33,.5,.67,.83), (0,0,.15,.5), (0,0,.15,.5)	(.33,.5,.67,.83), (.5,.67,.67,.83), (.33,.5,.5,.67), (.33,.5,.5,.67)	(0,0,0,.17), (0,0,.03,.33), (0,.17,.33,.5), (0,0,.03,.33)	(.33,.5,.67,.83), (.67,.83,.83,1), (.5,.67,.67,.83), (.33,.5,.67,.83)	(0,0,.35,.67), (0,0,.15,.5), (.17,.33,.33,.5), (.33,.5,.5,.67)	(.67,.97,1,1), (.5,.67,.67,.83), (.33,.5,.5,.67), (.33,.5,.5,.67)	(.67,.83,1,1), (.17,.33,.5,.67), (.5,.67,.67,.83), (.5,.67,.67,.83)
C2	(.33,.65,1,1), (.33,.64,.7,1), (.5,.67,.67,.83), (0,0,.15,.5)		(.33,.5,.67,.83), (.33,.64,.7,1), (.33,.5,.67,.83), (.33,.5,.67,.83)	(.67,.83,.83,1), (.5,.67,.67,.83), (.5,.67,.67,.83), (.5,.67,.67,.83)	(.33,.5,.5,.67), (0,.3,.36,.67), (.33,.5,.5,.67), (.33,.5,.67,.83)	(.17,.33,.33,.5), (.17,.33,.33,.5), (0,0,.15,.5), (0,0,0,.17)	(.33,.5,.67,.83), (.5,.67,.83,1), (0,0,.35,.67), (.33,.5,.5,.67)	(.33,.65,1,1), (.5,.67,.67,.83), (.17,.33,.5,.67)	(.67,.97,1,1), (.5,.85,1,1), (.5,.67,.67,.83), (.33,.5,.67,.83)	(.67,.83,.83,1), (.67,.83,.83,1), (.5,.67,.67,.83), (.5,.67,.67,.83)
C3	(0,.17,.33,.5), (.33,.5,.67,.83), (.5,.8,.86,1), (.33,.5,.67,.83)	(0,0,0,.17), (0,0,.03,.33), (0,0,0,.17), (0,0,0,.17)		(.67,.97,1,1), (.33,.64,.7,1), (.17,.47,.53,.83), (.5,.67,.83,1)	(.33,.5,.67,.83), (0,0,.35,.67), (.5,.67,.67,.83), (.33,.5,.67,.83)	(0,0,0,.17), (0,0,.03,.33), (0,0,.03,.33), (0,0,0,.17)	(.33,.65,1,1), (.17,.33,.33,.5), (.33,.5,.5,.67), (0,.17,.17,.33)	(0,.17,.33,.5), (.17,.33,.5,.67), (0,0,.03,.33), (0,.17,.17,.33)	(.67,.83,1,1), (.67,.97,1,1), (.67,.83,.83,1), (.5,.67,.67,.83)	(.5,.67,.83,1), (.33,.5,.67,.83), (.33,.5,.5,.67), (.5,.67,.67,.83)
C4	(.33,.5,.67,.83), (.33,.65,1,1), (0,0,.15,.5), (.5,.67,.67,.83)	(0,0,0,.17), (.33,.65,1,1), (0,0,.03,.33), (.17,.33,.33,.5)	(.33,.5,.67,.83), (.5,.67,.67,.83), (.33,.5,.67,.83), (.17,.47,.53,.83)		(.67,.83,.83,1), (.5,.67,.67,.83), (.5,.67,.83,1), (.5,.67,.67,.83)	(.5,.67,.83,1), (.33,.5,.67,.83), (0,0,.15,.5), (.33,.5,.67,.83)	(.33,.5,.67,.83), (.33,.65,1,1), (.33,.5,.5,.67), (.17,.33,.33,.5)	(0,.3,.36,.67), (.17,.47,.53,.83), (0,0,.35,.67), (.33,.5,.67,.83)	(.17,.33,.5,.67), (.33,.5,.5,.67), (0,0,.15,.5), (.33,.5,.5,.67)	(0,0,.15,.5), (.33,.5,.5,.67), (.17,.33,.33,.5), (.17,.33,.33,.5)
C5	(.33,.5,.67,.83), (.17,.47,.53,.83), (.5,.67,.67,.83), (.67,.83,.83,1)	(0,0,0,.17), (0,0,.03,.33), (0,0,0,.17), (0,0,0,.17)	(.33,.5,.67,.83), (.33,.5,.5,.67), (0,0,.15,.5), (.33,.5,.5,.67)	(.5,.67,.83,1), (.17,.47,.53,.83), (.17,.33,.33,.5), (0,0,.35,.67)		(0,0,0,.17), (0,.17,.17,.33), (0,0,.03,.33), (0,0,0,.17)	(.17,.33,.5,.67), (.33,.5,.5,.67), (.17,.33,.33,.5), (.33,.5,.67,.83)	(0,0,0,.17), (0,.17,.17,.33), (.17,.33,.33,.5), (0,0,0,.17)	(.17,.33,.5,.67), (.67,.97,1,1), (0,.17,.17,.33), (0,0,0,.17)	(.17,.33,.5,.67), (.5,.67,.83,1), (0,.17,.17,.33), (.17,.33,.33,.5)
C6	(.5,.8,.86,1), (.67,.83,.83,1), (.67,.83,.83,1), (.5,.67,.83,1)	(.67,.97,1,1), (.5,.8,.86,1), (.5,.67,.67,.83), (.67,.83,.83,1)	(.83,1,1,1), (.5,.85,1,1), (.67,.83,.83,1), (.83,1,1,1)	(.5,.67,.83,1), (0,0,.15,.5), (0,0,.15,.5), (.17,.33,.33,.5)	(.5,.67,.83,1), (.17,.47,.53,.83), (.33,.65,1,1), (.67,.83,.83,1)		(.67,.83,.83,1), (.33,.5,.5,.67), (.5,.67,.67,.83), (.5,.67,.67,.83)	(.5,.85,1,1), (.33,.5,.5,.67), (.67,.97,1,1), (.33,.64,.7,1)	(.67,.83,.83,1), (.5,.85,1,1), (.67,.97,1,1), (.67,.83,.83,1)	(.67,.97,1,1), (.67,.97,1,1), (.5,.67,.83,1), (.67,.97,1,1)
C7	(.33,.5,.67,.83), (.33,.5,.5,.67), (.5,.67,.67,.83), (.33,.5,.5,.67)	(0,0,0,.17), (0,0,0,.17), (0,0,0,.17), (0,0,0,.17)	(0,0,.17,.33), (0,0,.03,.33), (0,0,.03,.33), (0,0,.03,.33)	(.17,.33,.5,.67), (0,0,.15,.5), (.33,.5,.67,.83), (.33,.5,.67,.83)	(0,.3,.36,.67), (0,0,.03,.33), (0,0,.15,.5), (.5,.67,.67,.83)	(0,0,0,.17), (0,.17,.17,.33), (0,0,0,.17), (0,.17,.17,.33)		(.17,.33,.5,.67), (0,0,.03,.33), (.17,.33,.5,.67), (.5,.67,.67,.83)	(.33,.5,.5,.67), (0,.17,.33,.5), (0,0,0,.17), (.17,.33,.33,.5)	(.33,.5,.5,.67), (0,0,0,.17), (0,0,0,.17), (.33,.5,.5,.67)
C8	(.5,.85,1,1), (0,0,0,.17), (.5,.67,.83,1), (.33,.5,.67,.83)	(0,.17,.33,.5), (0,.17,.17,.33), (0,0,.17,.33), (.5,.67,.67,.83)	(.5,.67,.67,.83), (.33,.5,.67,.83), (.33,.64,.7,1), (.5,.67,.83,1)	(.33,.5,.5,.67), (0,0,.35,.67), (.33,.5,.5,.67), (.5,.67,.67,.83)	(0,0,.17,.33), (0,0,0,.17), (0,0,.15,.5), (0,0,.03,.33)	(.17,.47,.53,.83), (.17,.33,.5,.67), (.33,.5,.67,.83), (.33,.5,.5,.67)	(0,.17,.17,.33), (0,.17,.17,.33), (.5,.67,.67,.83), (.17,.33,.33,.5)		(.5,.85,1,1), (.33,.5,.67,.83), (.33,.64,.7,1), (.5,.67,.67,.83)	(.83,1,1,1), (.5,.67,.83,1), (.5,.85,1,1), (.17,.47,.53,.83)
C9	(.67,.97,1,1), (.33,.5,.67,.83),	(0,0,.17,.33), (0,.17,.17,.33),	(.33,.64,.7,1), (.33,.5,.67,.83),	(.5,.67,.83,1), (.5,.67,.67,.83),	(.33,.5,.5,.67), (0,0,.15,.5),	(0,0,0,.17), (.33,.5,.67,.83),	(.33,.65,1,1), (.33,.5,.67,.83),	(0,0,0,.17), (.17,.33,.33,.5),		(.33,.5,.5,.67), (0,0,.35,.67),

(*continued on next page*)

(*continued*)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C10	(.5,.67,.67,.83), (.5,.67,.67,.83) (.17,.47,.53,.83), (.5,.85,1,1), (.5,.67,.67,.83), (.67,.83,.83,1)	(0,0,0,.17), (0,0,0,.17) (0,0,0,.17), (0,.17,.33,.5), (0,.17,.17,.33), (.5,.67,.67,.83)	(.5,.85,1,1), (.33,.5,.67,.83) (.5,.85,1,1), (.5,.67,.83,1), (.5,.67,.67,.83), (.67,.83,.83,1)	(.33,.5,.5,.67), (.5,.67,.67,.83) (.5,.85,1,1), (.17,.33,.5,.67), (.5,.85,1,1), (.5,.67,.67,.83)	(0,0,0,.17), (0,0,.15,.5) (0,0,.35,.67), (0,0,.15,.5), (.33,.5,.67,.83), (.33,.5,.67,.83)	(0,0,.03,.33), (0,0,0,.17) (0,0,0,.17), (0,.17,.17,.33), (.33,.5,.5,.67), (0,0,.03,.33)	(0,.17,.17,.33), (.5,.67,.67,.83) (.33,.5,.67,.83), (.33,.5,.5,.67), (.33,.5,.67,.83), (.5,.67,.67,.83)	(0,0,0,.17), (.5,.67,.67,.83) (.5,.85,1,1), (.33,.5,.5,.67), (.5,.67,.67,.83), (.5,.67,.67,.83)	(.5,.8,.86,1), (.5,.85,1,1), (.5,.67,.83,1), (.5,.67,.83,1)	(.5,.85,1,1), (.33,.5,.67,.83)

Appendix 5. Expert Opinion Information Aggregation Matrix

	C1	C2	C3	C4	C5
C1		(0,0,.011,.33)	(.17,.566,.6,1)	(0,.436,.559,1)	(.17,.5,.568,.83)
C2	(0,.492,.638,1)		(.33,.556,.743,1)	(.5,.738,.768,1)	(0,.426,.506,.83)
C3	(0,.494,.606,1)	(0,0,.11,.33)		(.17,.683,.78,1)	(0,.4,.573,.83)
C4	(0,.497,.632,1)	(0,.229,0.306,1)	(.17,.527,.609,.83)		(.5,.702,.734,1)
C5	(.17,.593,.641,1)	(0,.034,.04,.33)	(0,.366,.464,.83)	(0,.393,.544,1)	
C6	(.5,.76,.804,1)	(.5,.82,.838,1)	(.5,.902,.932,1)	(0,.166,.291,.67)	(.17,.656,.805,1)
C7	(0,.434,.468,.83)	(0,0,0,.17)	(0,0,.051,.33)	(0,.3,.464,.83)	(0,.228,.308,.83)
C8	(0,.532,.641,1)	(0,.202,.302,.83)	(.33,.595,.709,1)	(0,.4,.471,.83)	(0,.066,.135,.5)
C9	(.33,.733,.802,1)	(0,.034,.068,.33)	(.33,.632,.743,1)	(.33,.602,.668,1)	(0,.166,.225,.67)
C10	(.17,.63,.707,1)	(0,.268,.3,.83)	(.5,.738,.8,1)	(.17,.675,.768,1)	(0,.234,.434,.83)
	C6	C7	C8	C9	C10
C1	(0,.034,.111,0.5)	(0,.534,.634,1)	(0,.2,.3,.67)	(.33,.694,.7,1)	(.17,.7,.768,1)
C2	(0,.266,.296,.83)	(0,.4,.571,1)	(.17,.724,.834,1)	(.33,.733,.834,1)	(.5,.766,.8,1)
C3	(0,.066,.077,.5)	(0,.422,.507,1)	(0,.168,.272,.67)	(.5,.826,.866,1)	(.17,.534,.634,1)
C4	(0,.334,.464,1)	(.17,.529,.634,1)	(0,.319,.484,.83)	(0,.366,.43,.67)	(0,.298,.328,.67)
C5	(0,.068,.074,.33)	(.17,.466,.566,1)	(0,.1,.1,.5)	(0,.262,.3,1)	(0,.334,.432,1)
C6		(.33,.668,.668,1)	(.33,.692,.775,1)	(.5,.831,.866,1)	(.5,.851,.932,1)
C7	(0,.102,.102,.33)		(0,.332,.406,.83)	(0,.3,.332,.67)	(0,.266,.266,0.67)
C8	(0,.359,.441,.83)	(0,.268,.302,.83)		(.33,.632,.743,1)	(.17,.732,.775,1)
C9	(0,.134,.174,.83)	(0,.431,.536,1)	(0,.2,.2,.83)		(0,.404,.539,1)
C10	(0,.168,.174,.67)	(.33,.534,.602,.83)	(.33,.638,.668,1)	(.5,.732,.87,1)	

Appendix 6. Initial total matrices of lower bound, upper bound and information matrices for $\alpha = 0.1$

	C1	C2	C3	C4	C5
C1	(0,0,0)	(0,0.298,0.149)	(0.21,0.96,0.585)	(0.044,0.956,0.5)	(0.203,0.804,0.503)
C2	(0.049,0.964,0.506)	(0,0,0)	(0.353,0.974,0.663)	(0.524,0.977,0.75)	(0.043,0.798,0.42)
C3	(0.049,0.961,0.505)	(0,0.298,0.149)	(0,0,0)	(0.221,0.978,0.6)	(0.04,0.804,0.422)
C4	(0.05,0.963,0.506)	(0.023,0.931,0.477)	(0.206,0.808,0.507)	(0,0,0)	(0.52,0.973,0.747)
C5	(0.212,0.964,0.588)	(0.003,0.301,0.152)	(0.037,0.793,0.415)	(0.039,0.954,0.497)	(0,0,0)
C6	(0.526,0.98,0.753)	(0.532,0.984,0.758)	(0.54,0.993,0.767)	(0.017,0.632,0.324)	(0.219,0.98,0.6)
C7	(0.043,0.794,0.419)	(0,0.153,0.077)	(0,0.302,0.151)	(0.03,0.793,0.412)	(0.023,0.778,0.4)
C8	(0.053,0.964,0.509)	(0.02,0.777,0.399)	(0.357,0.971,0.664)	(0.04,0.794,0.417)	(0.007,0.464,0.235)
C9	(0.37,0.98,0.675)	(0.003,0.304,0.154)	(0.36,0.974,0.667)	(0.357,0.967,0.662)	(0.017,0.626,0.321)
C10	(0.216,0.971,0.593)	(0.027,0.777,0.402)	(0.524,0.98,0.752)	(0.22,0.977,0.599)	(0.023,0.79,0.407)
	C6	C7	C8	C9	C10
C1	(0.003,0.461,0.232)	(0.053,0.963,0.508)	(0.02,0.633,0.327)	(0.366,0.97,0.668)	(0.223,0.977,0.6)
C2	(0.027,0.777,0.402)	(0.04,0.957,0.499)	(0.225,0.983,0.604)	(0.37,0.983,0.677)	(0.527,0.98,0.753)
C3	(0.007,0.458,0.232)	(0.042,0.951,0.496)	(0.017,0.63,0.323)	(0.533,0.987,0.76)	(0.206,0.963,0.585)
C4	(0.033,0.946,0.49)	(0.206,0.963,0.585)	(0.032,0.795,0.414)	(0.037,0.646,0.341)	(0.03,0.636,0.333)
C5	(0.007,0.304,0.156)	(0.2,0.957,0.578)	(0.01,0.46,0.235)	(0.026,0.93,0.478)	(0.033,0.943,0.488)
C6	(0,0,0)	(0.364,0.967,0.665)	(0.366,0.977,0.672)	(0.533,0.987,0.76)	(0.535,0.993,0.764)
C7	(0.01,0.307,0.159)	(0,0,0)	(0.033,0.788,0.41)	(0.03,0.636,0.333)	(0.027,0.63,0.328)
C8	(0.036,0.791,0.414)	(0.027,0.777,0.402)	(0,0,0)	(0.36,0.974,0.667)	(0.226,0.977,0.602)
C9	(0.013,0.764,0.389)	(0.043,0.954,0.498)	(0.02,0.767,0.394)	(0,0,0)	(0.04,0.954,0.497)
C10	(0.017,0.62,0.319)	(0.35,0.807,0.579)	(0.361,0.967,0.664)	(0.523,0.987,0.755)	(0,0,0)

Appendix 7. Final total relationship matrices for lower, upper and information matrices for $\alpha = 0.1$

	C1	C2	C3	C4	C5
C1	(0.024,0.548,0.19)	(0.001,0.348,0.122)	(0.087,0.597,0.279)	(0.036,0.624,0.258)	(0.065,0.544,0.232)
C2	(0.052,0.757,0.326)	(0.005,0.377,0.132)	(0.163,0.698,0.352)	(0.184,0.728,0.35)	(0.046,0.633,0.268)
C3	(0.039,0.65,0.268)	(0.002,0.349,0.123)	(0.036,0.497,0.192)	(0.085,0.627,0.273)	(0.027,0.545,0.221)
C4	(0.031,0.703,0.283)	(0.008,0.445,0.181)	(0.07,0.632,0.284)	(0.013,0.573,0.197)	(0.149,0.607,0.281)

(*continued on next page*)

(*continued*)

	C1	C2	C3	C4	C5
C5	(0.064,0.617,0.255)	(0.002,0.329,0.11)	(0.02,0.552,0.23)	(0.017,0.594,0.235)	(0.007,0.431,0.137)
C6	(0.201,0.765,0.394)	(0.151,0.483,0.26)	(0.252,0.706,0.401)	(0.087,0.701,0.323)	(0.093,0.656,0.318)
C7	(0.015,0.5,0.193)	(0.001,0.258,0.081)	(0.006,0.412,0.155)	(0.011,0.481,0.185)	(0.009,0.429,0.167)
C8	(0.039,0.696,0.285)	(0.008,0.426,0.171)	(0.131,0.643,0.311)	(0.039,0.652,0.264)	(0.013,0.549,0.207)
C9	(0.114,0.674,0.301)	(0.003,.364,0.131)	(0.123,0.621,0.302)	(0.114,0.646,0.29)	(0.029,0.547,0.216)
C10	(0.092,0.72,0.324)	(0.01,0.438,0.184)	(0.193,0.665,0.349)	(0.099,0.693,0.316)	(0.031,0.601,0.254)
	C6	C7	C8	C9	C10
C1	(0.003,0.409,0.145)	(0.031,0.636,0.259)	(0.015,0.52,0.2)	(0.13,0.62,0.301)	(0.072,0.618,0.27)
C2	(0.012,0.513,0.206)	(0.047,0.74,0.314)	(0.085,0.645,0.29)	(0.169,0.724,0.366)	(0.169,0.72,0.349)
C3	(0.004,0.41,0.146)	(0.028,0.636,0.258)	(0.014,0.521,0.201)	(0.169,0.622,0.314)	(0.066,0.617,0.268)
C4	(0.01,0.493,0.191)	(0.07,0.689,0.286)	(0.014,0.582,0.227)	(0.032,0.641,0.272)	(0.02,0.637,0.251)
C5	(0.003,0.372,0.12)	(0.06,0.605,0.247)	(0.006,0.476,0.168)	(0.021,0.586,0.248)	(0.016,0.584,0.231)
C6	(0.006,0.432,0.161)	(0.143,0.748,0.369)	(0.138,0.65,0.326)	(0.267,0.732,0.416)	(0.211,0.729,0.386)
C7	(0.003,0.307,0.1)	(0.003,0.404,0.123)	(0.011,0.425,0.164)	(0.014,0.461,0.187)	(0.01,0.458,0.173)
C8	(0.012,0.475,0.183)	(0.023,0.663,0.26)	(0.012,0.491,0.165)	(0.138,0.666,0.322)	(0.078,0.663,0.29)
C9	(0.006,0.456,0.174)	(0.027,0.658,0.268)	(0.012,0.554,0.219)	(0.037,0.54,0.213)	(0.029,0.638,0.266)
C10	(0.008,0.473,0.185)	(0.114,0.689,0.312)	(0.108,0.612,0.285)	(0.201,0.689,0.362)	(0.03,0.582,0.225)

Appendix 8. The values of Ri + Cj and Ri - Cj for different alpha-level

α-Level		Lower		Upper		Information	
		Ri + Cj	Ri - Cj	Ri + Cj	Ri - Cj	Ri + Cj	Ri - Cj
0	C1	0.862	−0.149	14.104	−1.282	5.332	−0.546
	C2	0.955	0.655	12.154	2.982	4.744	1.449
	C3	1.359	−0.625	13.383	−0.560	5.404	−0.602
	C4	0.849	−0.271	14.382	−0.318	5.427	−0.227
	C5	0.483	−0.242	12.605	−0.374	4.577	−0.307
	C6	1.449	1.449	12.782	2.357	5.268	1.728
	C7	0.404	−0.404	12.490	−2.645	4.494	−1.207
	C8	0.678	0.052	13.374	0.484	4.992	0.200
	C9	1.476	−0.681	13.983	−0.549	5.699	−0.600
	C10	1.353	0.216	14.438	−0.095	5.800	0.112
0.2	C1	1.395	−0.262	10.475	−1.072	4.842	−0.575
	C2	1.282	0.821	8.897	2.506	4.179	1.465
	C3	1.739	−0.597	9.971	−0.544	4.859	−0.576
	C4	1.350	−0.266	10.656	−0.317	4.889	−0.251
	C5	0.876	−0.266	9.142	−0.414	4.014	−0.334
	C6	1.778	1.516	9.459	2.187	4.690	1.755
	C7	0.847	−0.516	9.082	−2.078	3.977	−1.136
	C8	1.128	0.105	9.805	0.418	4.438	0.223
	C9	1.860	−0.689	10.362	−0.613	5.089	−0.639
	C10	1.818	0.155	10.766	−0.074	5.234	0.067
0.3	C1	1.649	−0.314	9.138	−0.995	4.629	−0.588
	C2	1.438	0.900	7.697	2.331	3.933	1.472
	C3	1.923	−0.584	8.714	−0.538	4.621	−0.565
	C4	1.589	−0.268	9.284	−0.318	4.656	−0.261
	C5	1.063	−0.276	7.867	−0.428	3.770	−0.345
	C6	1.935	1.549	8.235	2.125	4.439	1.766
	C7	1.057	−0.568	7.828	−1.869	3.753	−1.106
	C8	1.341	0.129	8.490	0.396	4.197	0.235
	C9	2.044	−0.695	9.028	−0.637	4.824	−0.655
	C10	2.040	0.125	9.412	−0.067	4.988	0.048
0.4	C1	1.895	−0.363	8.018	−0.931	4.434	−0.600
	C2	1.590	0.976	6.689	2.184	3.708	1.479
	C3	2.102	−0.571	7.660	−0.534	4.404	−0.555
	C4	1.822	−0.270	8.134	−0.320	4.442	−0.271
	C5	1.243	−0.284	6.799	−0.439	3.546	−0.356
	C6	2.087	1.582	7.208	2.073	4.209	1.777
	C7	1.259	−0.616	6.777	−1.693	3.548	−1.078
	C8	1.547	0.153	7.387	0.377	3.977	0.245
	C9	2.223	−0.702	7.909	−0.657	4.582	−0.671
	C10	2.256	0.096	8.275	−0.060	4.763	0.030
0.5	C1	2.134	−0.410	7.065	−0.877	4.254	−0.612
	C2	1.737	1.050	5.832	2.059	3.501	1.485
	C3	2.276	−0.559	6.762	−0.530	4.203	−0.546
	C4	2.047	−0.274	7.155	−0.322	4.246	−0.281
	C5	1.417	−0.291	5.891	−0.449	3.341	−0.365
	C6	2.236	1.615	6.335	2.029	3.997	1.787
	C7	1.456	−0.663	5.885	−1.543	3.360	−1.052

(*continued on next page*)

(*continued*)

α-Level		Lower		Upper		Information	
		Ri + Cj	Ri - Cj	Ri + Cj	Ri - Cj	Ri + Cj	Ri - Cj
	C8	1.746	0.175	6.448	0.363	3.774	0.255
	C9	2.397	−0.709	6.957	−0.674	4.359	−0.685
	C10	2.466	0.068	7.308	−0.055	4.556	0.013
0.6	C1	2.365	−0.456	6.244	−0.831	4.088	−0.622
	C2	1.880	1.121	5.093	1.952	3.309	1.491
	C3	2.446	−0.547	5.988	−0.527	4.018	−0.538
	C4	2.267	−0.279	6.312	−0.326	4.065	−0.290
	C5	1.586	−0.298	5.110	−0.457	3.151	−0.373
	C6	2.380	1.646	5.583	1.992	3.802	1.795
	C7	1.646	−0.708	5.117	−1.413	3.188	−1.028
	C8	1.938	0.197	5.639	0.351	3.586	0.265
	C9	2.566	−0.716	6.137	−0.690	4.153	−0.698
	C10	2.670	0.040	6.473	−0.051	4.364	−0.002
0.7	C1	2.590	−0.499	5.530	−0.791	3.935	−0.632
	C2	2.019	1.190	4.449	1.858	3.132	1.496
	C3	2.612	−0.536	5.315	−0.525	3.847	−0.530
	C4	2.480	−0.285	5.579	−0.330	3.898	−0.299
	C5	1.750	−0.304	4.431	−0.463	2.976	−0.380
	C6	2.520	1.678	4.929	1.959	3.621	1.804
	C7	1.830	−0.750	4.451	−1.300	3.028	−1.006
	C8	2.125	0.218	4.935	0.341	3.412	0.274
	C9	2.730	−0.724	5.423	−0.703	3.962	−0.710
	C10	2.868	0.013	5.746	−0.047	4.187	−0.016
0.8	C1	2.808	−0.541	4.904	−0.756	3.792	−0.642
	C2	2.154	1.256	3.883	1.776	2.967	1.501
	C3	2.773	−0.524	4.723	−0.523	3.688	−0.523
	C4	2.687	−0.291	4.936	−0.334	3.743	−0.308
	C5	1.908	−0.309	3.836	−0.469	2.814	−0.386
	C6	2.657	1.708	4.354	1.931	3.453	1.811
	C7	2.009	−0.791	3.866	−1.200	2.881	−0.986
	C8	2.306	0.238	4.316	0.334	3.251	0.283
	C9	2.890	−0.732	4.796	−0.715	3.785	−0.722
	C10	3.061	−0.014	5.107	−0.044	4.023	−0.029
0.9	C1	3.020	−0.581	4.349	−0.726	3.660	−0.651
	C2	2.286	1.321	3.382	1.704	2.813	1.505
	C3	2.930	−0.513	4.198	−0.522	3.540	−0.517
	C4	2.889	−0.298	4.366	−0.339	3.599	−0.316
	C5	2.062	−0.314	3.310	−0.473	2.663	−0.392
	C6	2.789	1.738	3.846	1.907	3.297	1.818
	C7	2.182	−0.831	3.350	−1.111	2.744	−0.967
	C8	2.482	0.257	3.768	0.329	3.101	0.292
	C9	3.045	−0.739	4.241	−0.726	3.620	−0.732
	C10	3.249	−0.040	4.539	−0.041	3.870	−0.041
1	C1	3.227	−0.620	3.855	−0.699	3.536	−0.659
	C2	2.414	1.384	2.934	1.639	2.670	1.510
	C3	3.083	−0.503	3.730	−0.521	3.401	−0.511
	C4	3.085	−0.305	3.859	−0.345	3.465	−0.324
	C5	2.211	−.318	2.842	−0.476	2.522	−0.397
	C6	2.918	1.767	3.393	1.885	3.151	1.825
	C7	2.350	−0.869	2.891	−1.032	2.616	−0.950
	C8	2.653	0.276	3.279	0.324	2.961	0.300
	C9	3.196	−0.747	3.746	−0.736	3.467	−0.742
	C10	3.431	−0.066	4.033	−0.039	3.727	−0.052

Appendix 9

MMDE Method

The MMDE method was invented to determine the threshold value in the DEMATEL method, which will help to draw the inter-relationship map. This method is based on determining the maximum mean de-entropy (Li and Tzeng, 2009).

Step VIII: Ordered triplets formation from total relation matrix.

The triplet contains the value, dispatch node number, and receiving node number, and it is arranged in descending order in the total relationship matrix in Appendix 10.

Step IX: Determination of the maximum mean DE entropy for the dispatch node set.

The entropy of the node can be calculated by using equation (12)

$$H(p_1, p_2, p_3, \ldots, p_n) = -\sum_{i=1}^{n} p_i \ln p_i \tag{12}$$

The de-entropy of the node can be determined by using equation (13)

$$H^D = H\left(\frac{1}{n}, \frac{1}{n}, \frac{1}{n}, \ldots, \frac{1}{n}\right) - H(p_1, p_2, p_3, \ldots, p_n) \tag{13}$$

Where $H\left(\frac{1}{n}, \frac{1}{n}, \frac{1}{n}, \ldots, \frac{1}{n}\right)$ is the maximum entropy if all the probabilities are equal?

The mean de-entropy can be calculated by using equation (14)

$$MDE_t^{Di} = \frac{H_i^{Di}}{N\left(T_i^{Di}\right)} \tag{14}$$

By taking the maximum value of MDE_t^{Di}, the maximum mean de-entropy of the dispatch node is determined. After that, the corresponding T_t^{Di} and T_{max}^{Di} is calculated.

The de-entropy (DE) and Mean De-entropy (MDE) values are calculated using equations (12)–(14) for all the dispatch nodes and are arranged in Appendix 11.

Maximum Mean de entropy for dispatch node $MDE_{tl}^{Di} = 0.0964$

Corresponding $T_{tl}^{Di} = \{6, 6, 6, 6, 10\} = \{6,10\}$

$$T_{maxl}^{Di} = \{(.289, 6, 9), (.220, 10, 9)$$

Step X: Determination of the maximum mean DE entropy for the receive node set.

The same procedure given in step IX is used for the computation of T_t^{Ri} and T_{max}^{Ri}.

The de-entropy (DE) and Mean De-entropy (MDE) values are calculated using equations (13)–(15) for all the receive nodes and are arranged in Appendix 12.

Maximum Mean de entropy for receiving node $MDE_{tl}^{Ri} = 0.0398$

Corresponding $T_{tl}^{Re} = \{9, 3, 10, 1, 9, 9, 4, 3, 10, 7, 3, 9, 8, 9, 9,3\} = \{9, 3, 10, 1, 4, 7, 8\}$

$$T_{maxl}^{Re} = \{(.289, 6, 9), (.277, 6, 3), (.250, 6, 10), (.246, 6, 1), (.210, 2, 4), (.196, 6, 7), (.176, 6, 8)\}$$

Step XI: Determination of Threshold value.

Now, determine T_l^{Th} which is the union set of T_{maxl}^{Di} and T_{maxl}^{Re}. So T_l^{Th} is given by

$$T_l^{Th} = \{(.289, 6, 9), (.277, 6, 3), (.250, 6, 10), (.246, 6, 1), (.220, 10, 9), (.210, 2, 4), (.196, 6, 7), (.176, 6, 8)\}$$

Threshold value = Minimum value of $T_l^{Th} = .176$

Likewise, the threshold values for information and upper matrices were computed as .321 and .441, respectively. After finding the threshold values for the lower, information, and upper matrix, the interrelationship maps are constructed by considering the values higher than the threshold values.

Appendix 10. Ordered triplets of lower total relationship matrix

	Di	Re	value	Di	Re	value	Di	Re	value	Di	Re	value	Di	Re	value
1	6	9	0.289	9	1	0.155	4	1	0.104	5	9	0.066	8	8	0.039
2	6	3	0.277	6	5	0.153	2	5	0.101	3	3	0.063	10	6	0.036
3	6	10	0.250	9	3	0.151	1	5	0.100	5	10	0.063	8	2	0.034
4	6	1	0.246	10	7	0.150	8	4	0.100	4	8	0.061	4	2	0.034
5	10	9	0.220	8	10	0.142	4	9	0.098	1	1	0.060	7	3	0.030
6	2	9	0.213	9	4	0.141	1	7	0.096	9	5	0.059	5	8	0.030
7	2	4	0.210	6	4	0.140	1	4	0.094	7	9	0.057	6	6	0.029
8	10	3	0.210	2	8	0.139	5	7	0.093	4	4	0.051	5	5	0.027
9	2	10	0.204	10	8	0.138	3	7	0.086	7	4	0.051	9	6	0.026
10	6	7	0.196	2	1	0.135	9	7	0.085	1	8	0.050	7	7	0.023
11	2	3	0.192	3	4	0.135	9	10	0.085	7	10	0.049	2	2	0.021
12	3	9	0.192	1	3	0.130	4	10	0.079	8	5	0.048	3	6	0.021
13	6	8	0.176	1	10	0.127	8	7	0.078	8	6	0.048	1	6	0.017
14	8	9	0.175	4	3	0.123	10	5	0.076	2	6	0.048	7	6	0.017
15	1	9	0.164	4	7	0.117	3	5	0.076	9	8	0.047	5	6	0.015
16	8	3	0.164	8	1	0.114	10	10	0.073	3	8	0.047	9	2	0.014
17	4	5	0.159	2	7	0.114	5	3	0.069	7	8	0.046	3	2	0.011
18	6	2	0.157	3	10	0.112	5	4	0.068	4	6	0.044	1	2	0.011
19	10	4	0.157	5	1	0.109	9	9	0.067	10	2	0.040	5	2	0.010
20	10	1	0.156	3	1	0.104	7	1	0.067	7	5	0.039	7	2	0.007

Appendix 11. De-entropy and mean de-entropy of dispatch nodes

DNE	DE	MDE	DNE	DE	MDE	DNE	DE	MDE	DNE	DE	MDE
1	0.0000	0.0000	26	0.2375	0.0297	51	0.0593	0.0066	76	0.0200	0.0020
2	0.0000	0.0000	27	0.2636	0.0329	52	0.0573	0.0064	77	0.0128	0.0013

(continued on next page)

(*continued*)

DNE	DE	MDE	DNE	DE	MDE	DNE	DE	MDE	DNE	DE	MDE
3	0.0000	0.0000	28	0.2637	0.0330	53	0.0551	0.0061	78	0.0138	0.0014
4	0.0000	0.0000	29	0.2695	0.0337	54	0.0557	0.0062	79	0.0147	0.0015
5	0.1927	0.0964	30	0.2738	0.0342	55	0.0529	0.0059	80	0.0099	0.0010
6	0.2310	0.0770	31	0.2343	0.0293	56	0.0555	0.0062	81	0.0104	0.0010
7	0.1429	0.0476	32	0.1962	0.0245	57	0.0382	0.0042	82	0.0121	0.0012
8	0.0589	0.0196	33	0.1754	0.0219	58	0.0271	0.0030	83	0.0137	0.0014
9	0.0378	0.0126	34	0.1394	0.0174	59	0.0238	0.0026	84	0.0150	0.0015
10	0.0690	0.0230	35	0.1197	0.0150	60	0.0806	0.0081	85	0.0118	0.0012
11	0.0624	0.0208	36	0.1097	0.0137	61	0.0744	0.0074	86	0.0084	0.0008
12	0.1496	0.0374	37	0.1163	0.0145	62	0.0741	0.0074	87	0.0094	0.0009
13	0.1815	0.0454	38	0.0965	0.0121	63	0.0709	0.0071	88	0.0075	0.0008
14	0.2334	0.0467	39	0.1459	0.0162	64	0.0701	0.0070	89	0.0070	0.0007
15	0.2625	0.0438	40	0.1365	0.0152	65	0.0691	0.0069	90	0.0049	0.0005
16	0.2109	0.0352	41	0.1269	0.0141	66	0.0680	0.0068	91	0.0054	0.0005
17	0.2344	0.0335	42	0.1355	0.0151	67	0.0444	0.0044	92	0.0046	0.0005
18	0.2744	0.0392	43	0.1253	0.0139	68	0.0453	0.0045	93	0.0036	0.0004
19	0.2567	0.0367	44	0.1208	0.0134	69	0.0300	0.0030	94	0.0025	0.0003
20	0.2551	0.0364	45	0.1159	0.0129	70	0.0306	0.0031	95	0.0014	0.0001
21	0.2777	0.0347	46	0.1108	0.0123	71	0.0203	0.0020	96	0.0013	0.0001
22	0.3117	0.0390	47	0.1098	0.0122	72	0.0187	0.0019	97	0.0011	0.0001
23	0.2700	0.0337	48	0.0809	0.0090	73	0.0189	0.0019	98	0.0009	0.0001
24	0.2764	0.0346	49	0.0755	0.0084	74	0.0206	0.0021	99	0.0005	0.0000
25	0.2570	0.0321	50	0.0649	0.0072	75	0.0204	0.0020	100	0.0000	0.0000

Appendix 12. De-entropy and mean de-entropy of receive nodes

RNE	DE	MDE	RNE	DE	MDE	RNE	DE	MDE	RNE	DE	MDE
1	0.0000	0.0000	26	0.1490	0.0166	51	0.1032	0.0115	76	0.1205	0.0120
2	0.0000	0.0000	27	0.1498	0.0166	52	0.1036	0.0115	77	0.1187	0.0119
3	0.0000	0.0000	28	0.1184	0.0132	53	0.1088	0.0121	78	0.1025	0.0103
4	0.0000	0.0000	29	0.1059	0.0118	54	0.1016	0.0113	79	0.0801	0.0080
5	0.0541	0.0135	30	0.1044	0.0116	55	0.0979	0.0109	80	0.0799	0.0080
6	0.1438	0.0360	31	0.1102	0.0122	56	0.0997	0.0111	81	0.0796	0.0080
7	0.1344	0.0269	32	0.1208	0.0134	57	0.1010	0.0112	82	0.0682	0.0068
8	0.1153	0.0231	33	0.1161	0.0129	58	0.1020	0.0113	83	0.0530	0.0053
9	0.0865	0.0173	34	0.1290	0.0143	59	0.1027	0.0114	84	0.0419	0.0042
10	0.0960	0.0160	35	0.1129	0.0125	60	0.1052	0.0117	85	0.0428	0.0043
11	0.1191	0.0199	36	0.1134	0.0126	61	0.1073	0.0119	86	0.0435	.0044
12	0.1591	0.0265	37	0.1063	0.0118	62	0.1091	0.0121	87	0.0355	0.0035
13	0.1677	0.0240	38	0.1054	0.0117	63	0.1106	0.0123	88	0.0360	0.0036
14	0.2161	0.0309	39	0.1092	0.0121	64	0.0978	0.0109	89	0.0303	0.0030
15	0.2667	0.0381	40	0.1162	0.0129	65	0.1006	0.0112	90	0.0306	0.0031
16	0.2784	0.0398	41	0.1258	0.0140	66	0.0974	0.0108	91	0.0225	0.0023
17	0.2863	0.0358	42	0.1081	0.0120	67	0.0997	0.0111	92	0.0186	0.0019
18	0.2892	0.0321	43	0.0985	0.0109	68	0.1000	0.0111	93	0.0161	0.0016
19	0.2564	0.0285	44	0.0992	0.0110	69	0.1018	0.0113	94	0.0149	0.0015
20	0.2242	0.0249	45	0.1031	0.0115	70	0.0926	0.0103	95	0.0148	0.0015
21	0.2177	0.0242	46	0.0982	0.0109	71	0.0940	0.0104	96	0.0089	0.0009
22	0.1857	0.0206	47	0.1010	0.0112	72	0.0919	0.0102	97	0.0047	0.0005
23	0.2031	0.0226	48	0.0997	0.0111	73	0.1537	0.0154	98	0.0020	0.0002
24	0.1708	0.0190	49	0.1015	0.0113	74	0.1299	0.0130	99	0.0005	0.0000
25	0.1603	0.0178	50	0.1057	0.0117	75	0.1241	0.0124	100	0.0000	0.0000

Data availability

Data will be made available on request.

References

Adel, H.M., Khaled, M., Yehya, M.A., Elsayed, R., Ali, R.S., Ahmed, F.E., 2024. Nexus among artificial intelligence implementation, healthcare social innovation, and green image of hospitals' operations management in Egypt. Cleaner Logistics and Supply Chain 11, 100156. https://doi.org/10.1016/j.clscn.2024.100156.

Agrawal, R., Yadav, V.S., Majumdar, A., Kumar, A., Luthra, S., Arturo Garza-Reyes, J., 2023. Opportunities for disruptive digital technologies to ensure circularity in Supply Chain: a critical review of drivers, barriers and challenges. Comput. Ind. Eng. 178. https://doi.org/10.1016/j.cie.2023.109140.

Aheleroff, S., Mostashiri, N., Xu, X., Zhong, R.Y., 2021. Mass Personalisation as a service in industry 4.0: a resilient response case study. Adv. Eng. Inf. 50. https://doi.org/10.1016/j.aei.2021.101438.

Alshahrani, R., Yenugula, M., Algethami, H., Alharbi, F., Goswami, S.S., Naveed, Q.N., et al., 2024. Establishing the fuzzy integrated hybrid MCDM framework to identify the key barriers to implementing artificial intelligence-enabled sustainable cloud system in an IT industry. Expert Syst. Appl. 238, 121732.

Apaydın, O., Aladağ, Z., 2022. Ranking the evaluation criteria of Hi-Fi audio systems and constricted information space: a novel method for determining the DEMATEL threshold value. Appl. Acoust. 190. https://doi.org/10.1016/j.apacoust.2021.108584.

Baddley, J., Rasheed, F.N., 2023. The Aga Khan Development Network's (AKDN) approach to supply chain carbon footprinting for healthcare providers. Cleaner Logistics and Supply Chain 7, 100109. https://doi.org/10.1016/j.clscn.2023.100109.

Beheshti, M., Amoozad Mahdiraji, H., Rocha-Lona, L., 2023. Transitioning drivers from linear to circular economic models: evidence of entrepreneurship in emerging nations. Manag. Decis. https://doi.org/10.1108/MD-02-2023-0279.

Bentahar, O., Benzidia, S., Bourlakis, M., 2023. A green supply chain taxonomy in healthcare: critical factors for a proactive approach. Int. J. Logist. Manag. 34 (1), 60–83. https://doi.org/10.1108/IJLM-04-2021-0240.

Betto, F., Garengo, P., 2023. A circular pathway for developing resilience in healthcare during pandemics. Int. J. Prod. Econ. 266. https://doi.org/10.1016/j.ijpe.2023.109036.

Bhattacharya, A., Srivastava, S., Majumdar, A., 2024. Circular supply chains in manufacturing—Quo vadis? Accomplishments, challenges and future opportunities. Bus. Strat. Environ. https://doi.org/10.1002/bse.3702.

Bressanelli, G., Pigosso, D.C.A., Saccani, N., Perona, M., 2021. Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: a literature review. J. Clean. Prod. 298. https://doi.org/10.1016/j.jclepro.2021.126819.

Calzolari, T., Genovese, A., Brint, A., 2021. The adoption of circular economy practices in supply chains – an assessment of European Multi-National Enterprises. J. Clean. Prod. 312. https://doi.org/10.1016/j.jclepro.2021.127616.

Dastjerdi, M., Keramati, A., Keramati, N., 2023. A novel framework for investigating organizational adoption of AI-integrated CRM systems in the healthcare sector; using a hybrid fuzzy decision-making approach. Telematics and Informatics Reports 11. https://doi.org/10.1016/j.teler.2023.100078.

Daú, G., Scavarda, A., Scavarda, L.F., Portugal, V.J.T., 2019. The healthcare sustainable supply chain 4.0: the circular economy transition conceptual framework with the corporate social responsibility mirror. Sustainability 11 (12). https://doi.org/10.3390/su11123259.

Dixit, A., Dutta, P., 2024. Critical success factors for the adoption of circular economy in sustainable healthcare waste management. Clean Technol. Environ. Policy 1–21.

Dohale, V., Ambilkar, P., Kumar, A., Mangla, S.K., Bilolikar, V., 2023. Analyzing the enablers of circular supply chain using Neutrosophic-ISM method: lessons from the Indian apparel industry. Int. J. Logist. Manag. 34 (3), 611–643. https://doi.org/10.1108/IJLM-03-2022-0141.

Dwivedi, A., Chowdhury, P., Agrawal, D., Paul, S.K., Shi, Y., 2023. Antecedents of digital supply chains for a circular economy: a sustainability perspective. Ind. Manag. Data Syst. 123 (6), 1690–1716. https://doi.org/10.1108/IMDS-05-2022-0273.

Dziedzic, M., Gomes, P.R., Angilella, M., El Asli, A., Berger, P., Charmier, A.J., et al., 2022. International circular economy strategies and their impacts on agricultural water use. Cleaner Engineering and Technology 8, 100504.

Erol, I., Peker, I., Ar, I.M., Searcy, C., 2023. Examining the role of urban-industrial symbiosis in the circular economy: an approach based on N-Force field theory of change and N-ISM-Micmac. Operations Management Research 16 (4), 2125–2147. https://doi.org/10.1007/s12063-023-00393-w.

Eti, S., Yüksel, S., Dinçer, H., Kalkavan, H., Hacioglu, U., Mikhaylov, A., et al., 2024. Assessment of technical and financial challenges for renewable energy project alternatives. Cleaner Engineering and Technology 18, 100719.

Fan, J., Yuan, J., Wu, M., 2024. A novel fuzzy DEMATEL method based on social network analysis and α-level sets considering experts' hesitant information. https://doi.org/10.21203/rs.3.rs-3487564/v1.

Ferrari, A.A., Bogner, K., Palacio, V., Crisostomo, D., Seeber, N., Ebersberger, B., 2023. The COVID-19 pandemic as a window of opportunity for more sustainable and circular supply chains. Cleaner Logistics and Supply Chain 7, 100101. https://doi.org/10.1016/j.clscn.2023.100101.

Fobbe, L., Hilletofth, P., 2023. Moving toward a circular economy in manufacturing organizations: the role of circular stakeholder engagement practices. Int. J. Logist. Manag. 34 (3), 674–698. https://doi.org/10.1108/IJLM-03-2022-0143.

Govindan, K., Bouzon, M., 2018. From a literature review to a multi-perspective framework for reverse logistics barriers and drivers. In *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2018.03.040.

Govindan, K., Hasanagic, M., 2018. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. Int. J. Prod. Res. 56 (1–2), 278–311. https://doi.org/10.1080/00207543.2017.1402141.

Gue, I.H.V., Promentilla, M.A.B., Tan, R.R., Ubando, A.T., 2020. Sector perception of circular economy driver interrelationships. J. Clean. Prod. 276. https://doi.org/10.1016/j.jclepro.2020.123204.

Hart, J., Adams, K., Giesekam, J., Tingley, D.D., Pomponi, F., 2019. Barriers and drivers in a circular economy: the case of the built environment. Procedia CIRP 80, 619–624. https://doi.org/10.1016/j.procir.2018.12.015.

Heeres, T., Tran, T., & Noort, A. (n.d.). Drivers and Barriers to Implementing Internet of Things in the Healthcare Supply Chain: Multi-Case Study. https://doi.org/10.2196/preprints.48730.

Hina, M., Chauhan, C., Kaur, P., Kraus, S., Dhir, A., 2022. Drivers and barriers of circular economy business models: where we are now, and where we are heading. J. Clean. Prod. 333. https://doi.org/10.1016/j.jclepro.2021.130049.

Hossain, M.K., Thakur, V., 2022. Drivers of sustainable healthcare supply chain performance: multi-criteria decision-making approach under grey environment. Int. J. Qual. Reliab. Manag. 39 (3), 859–880. https://doi.org/10.1108/IJQRM-03-2021-0075.

Hossain, M.K., Thakur, V., 2024. The promulgation of group purchasing organizations into the healthcare sector in India. Int. J. Pharmaceut. Healthc. Market. 18 (1), 86–101. https://doi.org/10.1108/IJPHM-12-2022-0108.

Hoveling, T., Nijdam, A.S., Monincx, M., Faludi, J., Bakker, C., 2024. Circular economy for medical devices: barriers, opportunities and best practices from a design perspective. Resour. Conserv. Recycl. 208, 107719.

Hsieh, Y.F., Lee, Y.C., Lin, S. Bin, 2016. Rebuilding DEMATEL threshold value: an example of a food and beverage information system. SpringerPlus 5 (1). https://doi.org/10.1186/s40064-016-3083-7.

Hussain, M., Ajmal, M.M., Gunasekaran, A., Khan, M., 2018. Exploration of social sustainability in healthcare supply chain. J. Clean. Prod. 203, 977–989. https://doi.org/10.1016/j.jclepro.2018.08.157.

Jakhar, S.K., Mangla, S.K., Luthra, S., Kusi-Sarpong, S., 2019. When stakeholder pressure drives the circular economy: Measuring the mediating role of innovation capabilities. Manag. Decis. 57 (4), 904. https://doi.org/10.1108/MD-09-2018-0990, 9.

Jia, F., Yin, S., Chen, L., Chen, X., 2020. The circular economy in the textile and apparel industry: a systematic literature review. In *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.120728.

Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy - from review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 135, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034.

Kamble, S., Belhadi, A., Gupta, S., Islam, N., Verma, V.K., Solima, L., 2023. Analyzing the barriers to building a 3-D printing enabled local medical supply chain ecosystem. IEEE Trans. Eng. Manag. https://doi.org/10.1109/TEM.2022.3226658.

Karamat, J., Shurong, T., Ahmad, N., Afridi, S., Khan, S., Khan, N., 2019. Developing sustainable healthcare systems in developing countries: Examining the role of barriers, enablers and drivers on knowledge management adoption. Sustainability 11 (4). https://doi.org/10.3390/su11040954.

Karloopia, J.J., Agrawal, R., 2024. Identifying and modeling barriers to design thinking implementation in healthcare sector: an ISM-MICMAC approach. J. Health Organisat. Manag.

Kayikci, Y., Kazancoglu, Y., Gozacan-Chase, N., Lafci, C., 2022a. Analyzing the drivers of smart sustainable circular supply chain for sustainable development goals through stakeholder theory. Bus. Strat. Environ. 31 (7), 3335–3353. https://doi.org/10.1002/bse.3087.

Kayikci, Y., Kazancoglu, Y., Lafci, C., Gozacan-Chase, N., Mangla, S.K., 2022b. Smart circular supply chains to achieving SDGs for post-pandemic preparedness. J. Enterprise Inf. Manag. 35 (1), 237–265. https://doi.org/10.1108/JEIM-06-2021-0271.

Kazancoglu, Y., Kazancoglu, I., Sagnak, M., 2018. Fuzzy DEMATEL-based green supply chain management performance: application in cement industry. Ind. Manag. Data Syst. 118 (2), 412–431.

Khan, F., Ali, Y., 2022. Implementation of the circular supply chain management in the pharmaceutical industry. Environ. Dev. Sustain. 24 (12), 13705–13731. https://doi.org/10.1007/s10668-021-02007-6.

Khan, S., Khan, M.I., Haleem, A., 2019. Evaluation of barriers in the adoption of halal certification: a fuzzy DEMATEL approach. J. Model. Manag. 14 (1), 153–174.

Khan, S.A., Mubarik, M.S., Paul, S.K., 2022. Analyzing cause and effect relationships among drivers and barriers to circular economy implementation in the context of an emerging economy. J. Clean. Prod. 364. https://doi.org/10.1016/j.jclepro.2022.132618.

Khan, S., Haleem, A., Khan, M.I., 2022. A grey-based framework for circular supply chain management: a forward step towards sustainability. Manag. Environ. Qual. Int. J. 33 (6), 1476–1501. https://doi.org/10.1108/MEQ-11-2021-0265.

Khan, S., Haleem, A., Khan, M.I., 2024. Enablers to implement circular initiatives in the supply chain: a grey DEMATEL method. Global Bus. Rev. 25 (1), 68–84.

Kumar, A., Chhabra, D., 2022. Adopting additive manufacturing as a cleaner fabrication framework for topologically optimized orthotic devices: implications over sustainable rehabilitation. Cleaner Engineering and Technology 10, 100559.

Lahane, S., Kant, R., 2021. Evaluating the circular supply chain implementation barriers using Pythagorean fuzzy AHP-DEMATEL approach. Cleaner Logistics and Supply Chain 2, 100014. https://doi.org/10.1016/j.clscn.2021.100014.

Lahane, S., Kant, R., 2021a. A hybrid Pythagorean fuzzy AHP – CoCoSo framework to rank the performance outcomes of circular supply chain due to adoption of its enablers. Waste Manag. 130, 48–60. https://doi.org/10.1016/j.wasman.2021.05.013.

Lahane, S., Prajapati, H., Kant, R., 2021. Evaluating and ranking the circular supply chain implementation enablers. Journal of Engineering Research (Kuwait) 2021. https://doi.org/10.36909/jer.ICIPPSD.15531.

Lahane, S., Gupta, P., Kant, R., 2022. Evaluating the benefits of circular economy due to adoption of its enablers. Manag. Environ. Qual. Int. J. 33 (2), 330–352. https://doi.org/10.1108/MEQ-03-2021-0060.

Li, C.W., Tzeng, G.H., 2009. Identification of a threshold value for the DEMATEL method using the maximum mean de-entropy algorithm to find critical services provided by a semiconductor intellectual property mall. Expert Syst. Appl. 36 (6), 9891–9898. https://doi.org/10.1016/j.eswa.2009.01.073.

Liu, H., Rodríguez, R.M., 2014. A fuzzy envelope for hesitant fuzzy linguistic term set and its application to multicriteria decision making. Inf. Sci. 258, 220–238. https://doi.org/10.1016/j.ins.2013.07.027.

Macneill, A.J., Hopf, H., Khanuja, A., Alizamir, S., Bilec, M., Eckelman, M.J., Hernandez, L., McGain, F., Simonsen, K., Thiel, C., Young, S., Lagasse, R., Sherman, J.D., 2020. Transforming the medical device industry: road map to a circular economy. Health Aff. 39 (12), 2088–2097. https://doi.org/10.1377/hlthaff.2020.01118.

Mahmudah, R.S., Putri, D.I., Abdullah, A.G., Shafii, M.A., Hakim, D.L., Setiadipura, T., 2024. Developing a Multi-Criteria Decision-Making model for nuclear power plant location selection using Fuzzy Analytic Hierarchy Process and Fuzzy VIKOR methods focused on socio-economic factors. Cleaner Engineering and Technology 19, 100737.

Menon, R.R., Ravi, V., 2021. Analysis of enablers of sustainable supply chain management in electronics industries: the Indian context. Cleaner Engineering and Technology 5, 100302.

Moktadir, M.A., Rahman, T., Rahman, M.H., Ali, S.M., Paul, S.K., 2018. Drivers to sustainable manufacturing practices and circular economy: a perspective of leather industries in Bangladesh. J. Clean. Prod. 174, 1366–1380. https://doi.org/10.1016/j.jclepro.2017.11.063.

Mondal, S., Singh, S., Gupta, H., 2023a. Assessing enablers of green entrepreneurship in circular economy: an integrated approach. J. Clean. Prod. 388. https://doi.org/10.1016/j.jclepro.2023.135999.

Mondal, S., Singh, S., Gupta, H., 2023b. Green entrepreneurship and digitalization enabling the circular economy through sustainable waste management - an exploratory study of emerging economy. J. Clean. Prod. 422. https://doi.org/10.1016/j.jclepro.2023.138433.
Mura, M., Longo, M., Zanni, S., 2020. Circular economy in Italian SMEs: a multi-method study. J. Clean. Prod. 245. https://doi.org/10.1016/j.jclepro.2019.118821.
Nag, U., Sharma, S.K., Govindan, K., 2021. Investigating drivers of circular supply chain with product-service system in automotive firms of an emerging economy. J. Clean. Prod. 319. https://doi.org/10.1016/j.jclepro.2021.128629.
Nagariya, R., Kumar, D., Kumar, I., 2021. Enablers to implement sustainable practices in the service only supply chain: a case of an Indian hospital. Bus. Process Manag. J. 27 (5), 1463–1495. https://doi.org/10.1108/BPMJ-10-2020-0469.
Orji, I.J., U-Dominic, C.M., Okwara, U.K., 2022. Exploring the determinants in circular supply chain implementation in the Nigerian manufacturing industry. Sustain. Prod. Consum. 29, 761–776. https://doi.org/10.1016/j.spc.2021.11.023.
Parmar, P.S., Desai, T.N., 2020. Evaluating Sustainable Lean Six Sigma enablers using fuzzy DEMATEL: a case of an Indian manufacturing organization. J. Clean. Prod. 265, 121802.
Patel, M.N., Pujara, A.A., Kant, R., Malviya, R.K., 2021. Assessment of circular economy enablers: hybrid ISM and fuzzy MICMAC approach. J. Clean. Prod. 317. https://doi.org/10.1016/j.jclepro.2021.128387.
Qazi, A.A., Appolloni, A., 2022. A systematic review on barriers and enablers toward circular procurement management. Sustain. Prod. Consum. 33, 343–359. https://doi.org/10.1016/j.spc.2022.07.013. Elsevier B.V.
Richter, J.L., Koppejan, R., 2016. Extended producer responsibility for lamps in Nordic countries: best practices and challenges in closing material loops. J. Clean. Prod. 123, 167–179. https://doi.org/10.1016/j.jclepro.2015.06.131.
Sabale, D.B., Kaswan, M.S., Rathi, R., Yadav, V., 2023. Investigating and modeling the circular economy enablers in product development process: net zero as a moderator. Benchmarking. https://doi.org/10.1108/BIJ-06-2023-0401.
Sankar, M.K., Gupta, S., Luthra, S., Jagtap, S., Singh, S., Kumar, A., 2024. The emergence of digitalization to the manufacturing sector in the sustainability context: a multi-stakeholder perspective analysis. J. Clean. Prod. 468, 142983.
Sharma, M., Joshi, S., Kumar, A., 2020. Assessing enablers of e-waste management in circular economy using DEMATEL method: an Indian perspective. Environ. Sci. Pollut. Control Ser. 27 (12), 13325–13338. https://doi.org/10.1007/s11356-020-07765-w.
Singh, R., Bhanot, N., 2020. An integrated DEMATEL-MMDE-ISM-based approach for analysing the barriers of IoT implementation in the manufacturing industry. Int. J. Prod. Res. 58 (8), 2454–2476.
Song, W., Cao, J., 2017. A rough DEMATEL-based approach for evaluating interaction between requirements of product-service system. Comput. Ind. Eng. 110, 353–363.
Suleman, T., Ezema, I., Aderonmu, P., 2023. Challenges of circular design adoption in the Nigerian built environment: an empirical study. Cleaner Engineering and Technology 17, 100686.
Swain, S., Muduli, K., Kumar, A., Luthra, S., 2024. Analysis of barriers of mHealth adoption in the context of sustainable operational practices in health care supply chains. International Journal of Industrial Engineering and Operations Management 6 (2), 85–116.
Swarnakar, V., Bagherian, A., Singh, A.R., 2023. Prioritization of critical success factors for sustainable Lean Six Sigma implementation in Indian healthcare organizations using best-worst-method. TQM Journal 35 (3), 630–653. https://doi.org/10.1108/TQM-07-2021-0199.
Torkayesh, A.E., Hendiani, S., Walther, G., Venghaus, S., 2024. Fueling the future: overcoming the barriers to market development of renewable fuels in Germany using a novel analytical approach. Eur. J. Oper. Res. 316 (3), 1012–1033.
Torrado, A., Barbosa-Póvoa, A., 2022. Towards an optimized and sustainable blood supply chain network under uncertainty: a literature review. Cleaner Logistics and Supply Chain 3, 100028. https://doi.org/10.1016/j.clscn.2022.100028.
Tseng, M.L., Ha, H.M., Wu, K.J., Xue, B., 2022. Healthcare industry circular supply chain collaboration in Vietnam: vision and learning influences on connection in a circular supply chain and circularity business model. Int. J. Logist. Res. Appl. 25 (4–5), 743–768. https://doi.org/10.1080/13675567.2021.1923671.
Tseng, M.L., Tran, T.P.T., Fujii, M., Lim, M.K., Negash, Y.T., 2024. Modelling hierarchical circular supply chain management enablers in the seafood processing industry in Vietnam under uncertainties. Int. J. Logist. Res. Appl. 27 (1), 30–58. https://doi.org/10.1080/13675567.2021.1965105.
Tura, N., Hanski, J., Ahola, T., Ståhle, M., Piiparinen, S., Valkokari, P., 2019. Unlocking circular business: a framework of barriers and drivers. J. Clean. Prod. 212, 90–98. https://doi.org/10.1016/j.jclepro.2018.11.202.
Tyagi, S., 2023. Analytics in healthcare supply chain management in the new normal era: a review and future research agenda. In: Benchmarking. Emerald Publishing. https://doi.org/10.1108/BIJ-03-2023-0155.
Upadhyay, A., Shukla, A.C., 2024. Circular supply chain management: content analysis with specific drivers and barriers. International Journal of Industrial Engineering : Theory Applications and Practice 31 (1), 101–127. https://doi.org/10.23055/ijietap.2024.31.1.9379.
Vishwakarma, A., Dangayach, G.S., Meena, M.L., Gupta, S., Luthra, S., 2023. Adoption of blockchain technology enabled healthcare sustainable supply chain to improve healthcare supply chain performance. Manag. Environ. Qual. Int. J. 34 (4), 1111–1128. https://doi.org/10.1108/MEQ-02-2022-0025.
Wang, Y.M., 2009. Centroid defuzzification and the maximizing set and minimizing set ranking based on alpha level sets. Comput. Ind. Eng. 57 (1), 228–236.
Wang, X., Zhang, C., Deng, J., Su, C., Gao, Z., 2022. Analysis of factors influencing miners' unsafe behaviors in intelligent mines using a novel hybrid MCDM model. Int. J. Environ. Res. Publ. Health 19 (12), 7368.
Wang, C., Sun, Y., Lim, M.K., Ghadimi, P., Azadnia, A.H., 2023. An analysis of barriers for successful implementation of municipal solid waste management in Beijing: an integrated DEMATEL-MMDE-ISM approach. Ind. Manag. Data Syst. 123 (3), 931–966.
Yadav, G., Luthra, S., Jakhar, S.K., Mangla, S.K., Rai, D.P., 2020. A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: an automotive case. J. Clean. Prod. 254. https://doi.org/10.1016/j.jclepro.2020.120112.
Yuan, Z., Bi, J., Moriguichi, Y., 2006. The circular economy: a new development strategy in China. J. Ind. Ecol. 10 (Issues 1–2), 4–8. https://doi.org/10.1162/108819806775545321.
Zhang, Z.X., Wang, L., Wang, Y.M., Martínez, L., 2023. A novel alpha-level sets based fuzzy DEMATEL method considering experts' hesitant information. Expert Syst. Appl. 213, 11.



https://dspace.org/

Identifying enablers for a circular healthcare supply chain: an integrated fuzzy DEMATEL-MMDE approach with hesitant information

Agrawal, Deepak; Gupta, Sumit; Dusad, Chandni; Meena, M. L.; Dangayach, Govind Sharan ...

2025-02
Elsevier
https://doi.org/10.1016/j.clet.2025.100882
Agrawal D, Gupta S, Dusad C, et al., (2025) Identifying enablers for a circular healthcare supply chain: an integrated fuzzy DEMATEL-MMDE approach with hesitant information. Cleaner Engineering and Technology, Volume 24, February 2025, Article number 100882

Downloaded from a DSpace repository. https://dspace.org/