Environmental Science

AIMS Environmental Science, 11(4): 516–550.
DOI: 10.3934/environsci.2024026
Received: 30 March 2024
Revised: 25 June 2024
Accepted: 01 July 2024
Published: 16 July 2024

https://www.aimspress.com/journal/environmental

Research article

Evaluation and prioritization of barriers to the implementation of the eco-regenerative supply chains using fuzzy ZE-numbers framework in group decision-making

Zeynab Rezazadeh Salteh[1], Saeed Fazayeli[1] and Saeid Jafarzadeh Ghoushchi[2,*]

[1] Department of Industrial Engineering, Faculty of Engineering, Urmia University, Urmia, Iran
[2] Faculty of Industrial Engineering, Urmia University of Technology, Urmia, Iran

* **Correspondence:** Email: s.jafarzadeh@uut.ac.ir.

Abstract: In today's supply chain management, there is a growing emphasis on transitioning to environmentally sustainable practices. This paper aimed to identify and rank the barriers to the implementation of eco-regenerative supply chains. A novel integrated approach was proposed based on stepwise weighted assessment ratio analysis (SWARA) and the multi-attributive border approximation area (MABAC) method using ZE-fuzzy numbers. This approach aimed to address some of the limitations of the failure mode and effects analysis (FMEA) method, including lack of thorough prioritization and inability to make decisions about the importance of various failure factors in an uncertain environment. By combining fuzzy sets and considering the reliability levels of two distinct groups of decision-makers and experts, this proposed method offers a comprehensive evaluation framework. Following the determination of the risk priority number (RPN) by the FMEA method, risk factors were evaluated using ZE-SWARA, and barriers were ranked using the ZE-MABAC method to identify critical barriers and propose corrective actions. Furthermore, sensitivity analysis was conducted in this study to demonstrate the viability of the proposed method. This research contributes to the advancement of eco-regenerative supply chain management practices by offering a systematic and innovative approach to addressing environmental concerns and improving decision-making processes in uncertain environments.

Keywords: MABAC; SWARA; Eco-regenerative supply chains; ZE numbers; FMEA

1. Introduction

Supply chains, as one of the essential factors in the production and distribution of products, play a very important role in the global economy. However, in recent years, environmental issues and changes have become one of the main factors determining the structure and performance of supply chains [1]. Given this reality, implementing eco-regenerative supply chains is necessary and vital for preserving natural resources and sustainable development [2].

Given the changes in regulations, laws, lifestyle trends, and especially customer preferences and their consequences, organizations have adopted more secure methods for enhancing sustainable management at all levels of their supply chains [2]. In a competitive environment, organizations are no longer independent entities and are seeking diverse supply chain systems. However, supply chains can have detrimental effects on the environment [3]. Furthermore, with the growth of the global population and urbanization, along with the rapid increase in greenhouse gas emissions, environmental issues have attracted more attention worldwide. Governments and organizations are aware that these detrimental effects occur through traditional supply chains whose aim is to maximize profit [4]. In fact, traditional supply chains, due to their unbalanced use of natural resources and without considering environmental impacts, may cause serious harm to the environment. For example, excessive use of water, energy, and raw materials provides a basis for environmental degradation [5]. On the other hand, eco-regenerative supply chains, by adopting environmentally friendly measures and sustainable use of natural resources, strive to reduce negative impacts. These actions may include the use of renewable energy sources, material recycling, waste reduction, and conservation of natural resources [6]. This approach is presented to enhance and improve supply chains while preserving the environment and aims to create supply chains that are both industrially advantageous and environmentally friendly. However, considering the numerous environmental challenges we currently face, such as climate change and loss of biodiversity and resources, it is clear that a significant change in supply chain management is necessary [7].

To reduce the negative impacts of supply chains on the environment, the first step is to examine and evaluate new resources and methods [8]. This includes selecting resources and processes that interact with the environment in a sustainable and friendly manner. In other words, resources used in sourcing raw materials and products from natural sources should be chosen in a way that preserves the environment and recovers resources [9].

Shifting the focus from reducing damage to facilitating ecosystem restoration requires seeking new approaches to create supply chains capable of the regeneration and ecological preservation of ecosystems. This means that production and supply processes should be designed in a way that ensures the improvement of ecosystems and, as a result, contributes to the preservation of biodiversity and natural resources [10]. These actions require innovative decision-making strategies, effective implementation, and the establishment of appropriate policy frameworks to support these goals. These efforts not only help improve supply chains and preserve the environment but also contribute to the reconstruction and improvement of ecosystems [11].

The concept of environmentally sustainable supply chains has gained significant attention and importance in recent years, stemming from the need for sustainable and responsible actions in various industries [12]. Researchers have focused on optimizing supplier performance by maximizing profits, minimizing negative environmental impacts, improving product quality and service levels, and reducing economic and operational risks [13–15]. They have developed a multi-objective model using mixed integer programming to address constraints such as supply chain capacity, demand, flow balance, and budget constraints. Additionally, they have examined the concept of a closed-loop green supply chain to minimize greenhouse gas emissions and enhance competitiveness in the market [16]. The innovative approach of this study encompasses a wide range of decision variables that encompass inventory, market, and transportation factors in various scenarios. Azarkamand and Niloufar [17] conducted a study on the impact of green supply chain management on green performance at Isfahan Iron Melting Company and found a positive effect on environmental performance.

Alinejad and Javad [18] proposed a combined ANP and VIKOR method in green supply chain management for prioritizing customers of petroleum products in a multi-criteria environment. This study focused on optimizing supplier performance, minimizing negative environmental impacts, and improving product quality and service levels. Their innovative approaches encompassed a wide range of decision variables and scenarios to address constraints and enhance competitiveness in the market. They examined the importance of green supply chain management for environmental preservation and company performance, focusing on factors affecting green supply chains in companies producing chemical and detergent materials. Their quantitative study on 16 companies showed that external stimuli positively influence internal stimuli toward operational activities and highlighted the need for companies to adopt green practices for competitiveness. Soon et al. [19] used a multi-layered approach to optimize economic factors, environmental concerns, and pollutant reduction, examining the challenges of supply chain management from a competitive and environmentally conscious perspective. The research by Hafezalkotob [20] emphasized the use of green supply chains for energy saving and underscored the importance of government collaboration in implementing tariffs and achieving social, political, and environmental benefits.

Green supply chain management starts from design and production in the factory and extends to product recycling at the end, considering environmental concerns [21]. The main goal of green supply chains is to reduce waste in industrial systems to conserve energy and prevent hazardous materials from entering the environment [22]. Various sources indicate that green supply chain management, in terms of tangible benefits, leads to cost reduction for suppliers, cost reduction for producers, cost reduction for customers, and less resource consumption [23]. In terms of intangible benefits, green supply chain management helps overcome bias and negativity toward the environment, reduces supplier rejection, facilitates production for manufacturers, and fosters better alignment with society [24–26]. By examining studies in this field, it can be understood that the implementation of green supply chain management methods covers a wide range of supply chains, from green procurement management to integrated lifecycle with a flow from supplier to customer and reverse logistics [27]. The core focus of green supply chain management places full emphasis on resources and the environment, improving the supply chain from an environmental perspective. Although these models do exhibit progress, their primary objective often revolves around mitigating the adverse consequences rather than fostering comprehensive environmental enhancement. Thus, eco-regenerative supply chains offer a novel approach that surpasses traditional notions, thereby providing a new perspective.

Eco-regenerative supply chains are a new concept that goes beyond traditional green supply chains. While green supply chains focus on reducing environmental impact and sustainability, eco-regenerative supply chains take it a step further by actively restoring and regenerating natural ecosystems and resources. The key difference between the two lies in their approach toward sustainability. Green supply chains aim to minimize negative environmental impacts through practices such as reducing carbon emissions, using renewable energy sources, and implementing recycling programs [28,29]. On the other hand, eco-regenerative supply chains not only seek to minimize harm to the environment but also actively work toward restoring and regenerating ecosystems through practices such as reforestation, soil regeneration, and water conservation. By focusing on regenerating natural resources, eco-regenerative supply chains aim to create a positive impact on the environment and promote long-term sustainability. This approach not only benefits the planet but also has the potential to create a more resilient and thriving supply chain system. However, comparing and analyzing the characteristics of eco-regenerative supply chains versus green supply chains reveals that there are multiple obstacles to implementing this environmentally-based system [30].

This research is conducted to evaluate and rank the barriers to implementing eco-regenerative supply chains. In this study, advanced decision-making methods in uncertain environments are used. These methods serve as analytical and decision-making tools for managers and decision-makers in the field of environmental supply chains. In this research, various barriers that may exist in the implementation of eco-regenerative supply chains are identified, evaluated, and ranked. Subsequently, using decision-making methods in uncertain environments, prioritization of these barriers is carried out. This prioritization helps managers and decision-makers to choose the best solutions for overcoming barriers and implementing eco-regenerative supply chains. This research can assist managers and decision-makers in various industries to create environmental improvements in their supply chains using innovative and data-driven decision-making approaches, thereby contributing to the preservation and restoration of ecosystems. This research introduces an innovative decision support model, leveraging the SWARA and MABAC methods based on fuzzy ZE numbers. As the importance of implementing eco-regenerative supply chains continues to grow, this research aims to provide a comprehensive analysis of the barriers to implementation. By identifying and ranking these barriers, organizations can better understand the challenges they face and develop strategies to overcome them. This will ultimately help drive the adoption of more sustainable supply chain practices and contribute to a more environmentally friendly future.

The uniqueness of this model lies in its capacity to comprehensively evaluate barriers associated with the implementation of eco-regenerative supply chains. It achieves this by incorporating fuzzy sets and, notably, by considering the reliability levels of two distinct groups of decision makers (DMs) and experts. This dual consideration of the DMs and experts enhances the robustness and applicability of the decision support model. The main contributions of this research are as follows:

- Evaluating decision-makers individually engaged and analyzing their perspectives through different ways.
- Using the extended FMEA method aimed at overcoming barriers to eco-regenerative supply chains.
- Introducing a decision framework utilizing fuzzy sets and fuzzy ZE numbers for multiple criteria evaluation.
- Expanding the application of SWARA and MABAC methods with fuzzy ZE numbers to assess criteria and determine critical barriers.
- Serving as a valuable resource for senior managers and decision-makers in organizations and industries involved in eco-regenerative supply chains.
- Criterion weights are determined by a minimum number of pairwise comparisons to ensure full consistency of the resulting weights.

The remainder of this study is organized as follows: Section 2 conducts a literature review on barriers to eco-regenerative supply chains and identifies research gaps in previous studies. The methodology of the extended methods is detailed in Section 3. Section 4 provides the results of the barrier levels, criteria weights, and alternative rankings. Section 5 includes the discussion and presentation of sensitive and comparative analyses. Finally, Section 6 encompasses the conclusion, findings, limitations, and suggestions for future research.

2. Literature review

Environmental supply chains are systems that focus on preserving and supporting the environment in the design, production, transportation, storage, and distribution of products and services [31]. These types of supply chains strive to reduce negative impacts on the environment and use natural resources efficiently. Some of the actions taken in environmental supply chains include using renewable resources, reducing pollution, waste management, reducing greenhouse gas emissions, and increasing energy efficiency. These supply chains aim to balance economics, society, and the environment and consider innovative and sustainable approaches in their activities to preserve natural resources and enhance environmental quality [32,33]. Implementing eco-regenerative supply chains is crucial for creating a sustainable future for our planet. This approach focuses on not only minimizing the environmental impact of supply chains but also actively working to regenerate and restore ecosystems [34,35]. By incorporating principles of circular economy, renewable energy, and regenerative agriculture, companies can reduce waste, carbon emissions, and resource depletion [36,37]. On the other hand, the increasing volume of data has highlighted the limitations of traditional analytical methods in handling and interpreting large datasets, prompting researchers to develop more advanced techniques with enhanced capabilities for big data analysis [38]. Consequently, numerous studies have harnessed machine learning techniques to address diverse facets of supply chain management, including the identification of optimal replenishment strategies, segmentation of suppliers based on environmental criteria [39], and the facilitation of green supply chain evolution and emission reduction initiatives [40]. Moreover, the utilization of machine learning algorithms can contribute significantly to enhancing transparency in the supply chain [41], reducing risks [42], reducing waste [42], and sourcing practices [43].

One other key aspect of eco-regenerative supply chains is the use of renewable energy sources such as solar, wind, and hydroelectric power. By transitioning away from fossil fuels, companies can significantly reduce their carbon footprint and contribute to a cleaner environment. Ali et al. [44] investigated the management of green supply chains in a developing economy and the influence of corporate social responsibility departments on emission control in manufacturing firms in India, emphasizing the role of green practices like procurement and product designs. The study of Barman et al. [45] delved into a dual-channel green supply chain model, integrating marketing strategies like carbon reduction rates and delivery lead times to attract customers while implementing environmental protocols like carbon taxes and cap-and-trade systems. Lotfi et al. [46] emphasized the increasing use of renewable energy (RE) in supply chain network design (SCND) for resilience and sustainability. By integrating RE into supply chain pillars, the research introduced a novel approach, RSSCNDRE, using a two-stage robust stochastic optimization model to optimize facility locations and flow quantities, showcasing the economic feasibility and benefits of RE implementation for a resilient and sustainable supply chain. Goli et al. [47] addressed the significance of green supply chain network design and the rising transportation costs for manufacturing companies. It introduced an IoT-based, flexible, and sustainable supply chain model integrating forward/reverse logistics, showcasing the utilization of multi-objective mixed-integer linear programming and goal programming to optimize the network design under uncertainty. Aytekin et al. [48] emphasized the importance of sustainable supply chain management (SSCM) practices for business competitiveness and international market participation, showcasing the benefits of integrating sustainability into supply chain operations. By evaluating factors influencing SSCM performance in the textile industry using a neutrosophic approach, the research highlights the significance of performance management in decision-making, competitive advantage, and environmental responsibility.

Examining barriers to the implementation of eco-regenerative supply chains is crucial for achieving sustainability goals in today's global economy [49]. This review highlights the importance of identifying and addressing obstacles that hinder the adoption of eco-regenerative practices in supply chain management. One of the key barriers to implementing eco-regenerative supply chains is the lack of awareness among stakeholders. Many companies may not fully understand the benefits of adopting regenerative practices or may not be aware of the negative impact their current supply chain processes have on the environment. Educating stakeholders about the importance of eco-regenerative supply chains and the potential benefits they can bring is essential in overcoming this barrier [2]. Another major barrier is the high costs associated with transitioning to eco-regenerative supply chains. Implementing sustainable practices often requires significant investment in new technologies, training, and infrastructure. Companies may be reluctant to incur these costs, especially if they do not see immediate returns on their investment. Finding ways to reduce costs and demonstrate the long-term benefits of eco-regenerative practices is essential in overcoming this barrier [50,51].

Resistance to change is also a common barrier to implementing eco-regenerative supply chains. Employees and management may be hesitant to adopt new practices or may be comfortable with the status quo [52]. Overcoming this barrier requires strong leadership, effective communication, and a clear vision for the future of the supply chain. Table 1 summarizes the barriers to implementing eco-regenerative supply chains from the literature.

Table 1. Barriers to implementing eco-regenerative supply chains.

Barriers	Descriptive	Case study	Methods	References
. Financial . Management . Policy . Social . Cultural . Resistance to change	High initial costs and uncertain return on investment	Healthcare supply chains	Literature review, semi-structured interviews	[53]
. Technological . Market demand	Lack of advanced technology and infrastructure	Electronics industry	Interviews, surveys	[54]
. Operational barriers . Supply chain complexity	Complex supply chain operations and policies	IoT implementation in healthcare supply chains	Mixed methods multi-case study	[55]
. Knowledge and awareness barriers	Lack of understanding of eco-regenerative practices	China and global eco-design practices in GSCM	Systematic literature review	[56]
. Regulatory barriers . Socio-political barriers	Insufficient legislative support	Blockchain technology in Nigerian construction SCM	Exploratory factor analysis (EFA)	[57]
. Collaboration barriers . Data management barriers	Challenges in collaboration among supply chain management	AI implementation in SCM	Extensive literature review	[58]
. Society or public pressure . Lack of organizational participation	Prioritization of motivational factors for GSCM	Indian construction industries	Analytic hierarchy process approach	[59]
. Desire to reduce costs . Customers demand	Environmental strategies in costs and demand management	Product developing and manufacturing companies	Extensive literature review	[60]

3. Problem statement

The importance of focusing on eco-regenerative practices in supply chain management has been strongly emphasized in recent times. In traditional supply chain models, there is often a conflict between the goal of optimizing efficiency and applying environmentally friendly practices. However, considering the multitude of environmental compatibility challenges we currently face, such as climate change, biodiversity loss, and resource depletion, it is clear that a significant change in supply chain management is needed. Traditional supply chains, due to their unbalanced use of natural resources and disregard for environmental impacts, can cause serious harm to the environment. For example, excessive use of water, energy, and raw materials can contribute to environmental degradation [45]. On the other hand, eco-regenerative supply chains, by adopting environmentally compatible measures and sustainable use of natural resources, aim to reduce negative impacts. These actions may include using renewable energy sources, recycling materials, reducing waste production, and conserving natural resources. This approach is presented to enhance and improve supply chains while preserving the environment, striving to create supply chains that are both industrially advantageous and environmentally benign. The first step in reducing the negative impact of supply chains on the environment is researching and evaluating new resources and methods in the supply chain. This includes selecting resources and processes that operate in a sustainable and environmentally friendly manner, meaning choosing resources used in sourcing raw materials and products in a way that protects the environment. Shifting the focus from reducing harm to facilitating ecosystem restoration indicates that we need to seek new approaches to create supply chains capable of restoring and protecting ecosystems. This means that we should focus on designing production and supply processes in a way that enables ecosystem recovery, thereby helping preserve biodiversity and natural resources. These actions require innovative decision-making strategies, effective implementation, and the establishment of appropriate policy frameworks to support these goals. These efforts not only help improve supply chains and preserve the environment but also contribute to the restoration and enhancement of ecosystems. This research is being conducted to assess and rank the barriers to implementing eco-regenerative supply chains [4].

3.1. Identified barriers

Implementing an eco-regenerative supply chains faces significant barriers, as described below and synthesized in Table 2.

- Financial resource shortage for development (A1): The lack of financial resources can hinder the development and advancement of green and eco-friendly technologies in the supply chain. This issue can reduce the ability to attract capital and realize these technologies.
- High development and implementation costs (A2): The high costs of developing and implementing processes and environmentally friendly technologies can be a major barrier to the development and widespread use of these technologies in the supply chain, as significant investments may be required to realize and benefit from them.
- Fluctuations in the prices of natural resources and environmental raw materials (A3): Decreases in the prices of natural resources and environmental raw materials can hinder the development of green and environmentally friendly technologies, as these changes can lead to increased costs and unpredictable income.
- Lack of short-term economic benefits (A4): The lack of short-term economic benefits can impede the development of green and environmentally friendly technologies, as many of these technologies,

in addition to long-term natural benefits, require high initial investments and costs, resulting in low short-term returns.

- High costs of structural and cultural changes (A5): The high costs of structural and cultural changes can be a barrier to creating an environmentally sustainable supply chain, as these changes require significant time and financial investment and involve changes in internal and external processes, systems, and behavioral patterns.
- Need for long-term investment for financial returns (A6): The need for long-term investment to achieve financial returns from environmentally friendly technologies can be a major obstacle, as these technologies require substantial investment in time and high costs to understand and utilize them. These long periods and high costs may deter some investors from investing in these technologies.

Table 2. Barriers to the implementation of the eco-regenerative supply chains.

		Barriers
Economic	A1	Financial resource shortage for development
	A2	High development and implementation costs
	A3	Fluctuations in the prices of natural resources and environmental raw materials
	A4	Lack of short-term economic benefits
	A5	High costs of structural and cultural changes
	A6	Need for long-term investment for financial returns
	A7	Lack of support and shareholder participation
	A8	Negative economic impacts of environmental policy changes on the supply chain
Social	A9	Lack of awareness and knowledge about environmentally friendly technologies in society and organizations
	A10	Organizational culture resistance to change toward processes and technologies
	A11	Need for training and development of technical skills for technology implementation
	A12	Management's lack of commitment and support
	A13	Customer awareness and participation in environmentally compatible supply chain management activities
	A14	Need for coordination and collaboration among members of the environmentally friendly supply chain
	A15	Neglect and lack of attention to environmental and social issues
Environment	A16	Shortage of natural resources and environmental raw materials for use in environmentally friendly processes and technologies
	A17	Challenges related to sourcing environmentally friendly resources and raw materials
	A18	Need to use clean and green technologies to reduce negative environmental impacts
	A19	Technological and technical barriers to implementing processes and technologies
	A20	Adverse effects of climate change on supply chains and processes
	A21	Lack of government regulations and legal frameworks
Political	A22	Lack of preferred financial and economic policies to incentivize the use of environmentally friendly supply chains
	A23	Legal and environmental constraints
	A24	Need for implementing environmental management certifications and standards
	A25	Political and policy implications of changes in environmental policies
	A26	Lack of government guarantees and facilities for implementing processes
	A27	Need for coordination between government policies and organizations for development
	A28	Political and policy implications of changes in supply chain strategies on the environment

- Lack of support and shareholder participation (A7): Lack of support and participation from stakeholders can hinder the development of environmentally friendly technologies, as the development of these technologies requires financial support and participation from stakeholders including investors and organizations to secure financial and other resources. Lack of support and participation can limit and slow down the development of these technologies.
- Negative economic impacts of environmental policy changes on the supply chain (A8): Changes in environmental policies can lead to negative economic impacts on the supply chain, as these changes may require structural changes and major investments in processes and environmental technologies of companies, resulting in additional costs, reduced profits, and disruption of the supply chain.
- Lack of awareness and knowledge about environmentally friendly technologies in society and organizations (A9): Lack of awareness and knowledge about environmentally friendly technologies can be a barrier to the acceptance and utilization of these technologies in society and organizations, because lack of awareness of the benefits, performance, and methods of these technologies can create doubt and resistance in individuals and organizations, leading to inappropriate decision-making and underutilization of these technologies.
- Organizational culture resistance to change toward processes and technologies (A10): Organizational culture resistance to change toward environmentally friendly processes and technologies can hinder the progress and implementation of these technologies in organizations because it requires changes in beliefs, habits, and work methods. This resistance can lead to opposition and doubt among employees and organizations, slowing down and complicating the transition to environmentally friendly technologies.
- Need for training and development of technical skills for technology implementation (A11): The need for training and development of technical skills can be a barrier to implementing environmentally friendly technologies because these technologies require specific knowledge and skills in the field of technical and environmental technology that require training and preparation of employees and individuals engaged in the industry. Lack of development of necessary skills can slow down the implementation of these technologies and therefore hinder progress in the environmental sector.
- Management's lack of commitment and support (A12): Management's lack of commitment and support can be a barrier to implementing environmentally friendly processes and technologies because, for the successful implementation of these technologies, there is a need for strong commitment and support from managers and organizational leaders. Lack of commitment and appropriate support can lead to resource misallocation, neglect of benefits and expected outcomes, and deficiencies in implementing and monitoring environmentally friendly technologies.
- Customer awareness and participation in environmentally compatible supply chain management activities (A13): Customer awareness and participation can be a barrier to conducting environmentally compatible supply chain management activities because it requires customer awareness and active participation in preferring environmentally friendly products and services and prioritizing sustainable supply chain management. Customer participation can lead to a lack of demand and environmental profit margins and reduce incentives for companies to choose and implement environmentally friendly solutions.
- Need for coordination and collaboration among members of the environmentally friendly supply chain (A14): The need for coordination and collaboration among members of the supply chain can be a barrier to implementing environmentally friendly processes and technologies because these technologies require coordination and collaboration among producers, suppliers, distributors, and customers. Lack of coordination and collaboration can lead to information-transfer failures, operational delays, and non-implementation of environmentally friendly systems and processes in the

supply chain.

- Neglect and lack of attention to environmental and social issues (A15): Neglect and lack of attention to environmental and social issues can be a barrier to selecting and implementing supply chain processes and technologies because ignoring these issues can lead to negative environmental impacts, human rights violations, social injustice, and supply chain instability. This lack of attention can result in a lack of public trust, legal issues, and a focus on short-term benefits obtained from supply chain processes and technologies.
- Shortage of natural resources and environmental raw materials for use in environmentally friendly processes and technologies (A16): Shortage of natural resources and environmental raw materials can be a barrier to using environmentally friendly processes and technologies because the implementation of these technologies requires renewable natural resources and environmental raw materials. Inadequate supply of these resources and materials can restrict the development and use of environmentally friendly technologies and lead to problems such as reduced resource quality and availability, price increases, and environmental degradation.
- Challenges related to sourcing environmentally friendly resources and raw materials (A17): Challenges related to sourcing environmentally friendly resources and raw materials can be a barrier to using environmentally friendly processes and technologies because the inability to source renewable natural resources, depletion of environmental raw material inventory, and limited access to required resources can lead to implementation delays and cost increases. This can also impact the sustainability and continuity of environmentally friendly technologies.
- Need to use clean and green technologies to reduce negative environmental impacts (A18): The need to use clean and green technologies to reduce negative environmental impacts can be a barrier to successful environmental preservation because implementing these technologies requires the development and transfer of clean technologies, investment in research and development, and the creation of necessary infrastructure. The inability to use clean and green technologies can lead to increased pollution, depletion of natural resources, and climate change, hindering environmental preservation and quality of life improvement.
- Technological and technical barriers to implementing processes and technologies (A19): Technological and technical barriers can be a hindrance to implementing environmentally friendly processes and technologies because they require the development and improvement of innovative technologies, transfer of clean and green technologies, and creation of suitable infrastructure. Issues such as the inability to develop clean technologies, high costs, lack of alignment with existing processes, and the need for training and capacity building of employees can lead to delays in implementing and transferring environmentally friendly technologies and reducing negative environmental impacts.
- Adverse effects of climate change on supply chains and processes (A20): The adverse effects of climate change can be a barrier to supply chains and the implementation of environmentally friendly processes and technologies because climate change can lead to the instability of natural resources, changes in supply and demand patterns, increased environmental and economic risks, and the destruction of supply chain infrastructure. These effects can result in reduced product quality and diversity, increased costs, and the need to change and adapt processes and technologies to be environmentally friendly.
- Lack of government regulations and legal frameworks (A21): The lack of government regulations and legal frameworks can be a barrier to supply chains and the implementation of environmentally friendly processes and technologies because the absence of clear and comprehensive laws and regulations for environmental protection and regulation of supply chain activities can lead to

shortcomings in achieving environmental goals, lack of motivation for the development of environmentally friendly technologies, and neglect of environmental and social issues. This may result in non-compliance of processes and technologies with standards, the need for internal governance and regulations, and delays in implementing environmental changes.

- Lack of preferred financial and economic policies to incentivize the use of environmentally friendly supply chains (A22): The lack of preferred financial and economic policies can be a barrier to incentivizing the use of environmentally friendly supply chains because the absence of suitable financial facilities and economic incentives for companies and organizations can lead to neglect of environmental aspects, reduced profitability and economic efficiency, and suboptimal use of environmentally friendly technologies and methods. This can lead to investment uncertainty, reduced effectiveness of environmental measures, and the emergence of financial and economic barriers to implementing environmentally friendly supply chains.
- Legal and environmental constraints (A23): Legal and environmental constraints can be a barrier to using materials and processes compatible with the environment because environmental laws and regulations may impose strict conditions and limitations on the use of non-biodegradable materials and green processes. These constraints can lead to increased costs, the need to change processes and technologies, and the need to explore and use suitable alternatives.
- Need for implementing environmental management certifications and standards (A24): The need for implementing environmental management certifications and standards can be a barrier to the supply chain as obtaining these certifications and complying with environmental management standards requires financial costs, time, and human resources. This need can lead to increased costs, the need to change processes and management systems, and increased complexity in the supply chain.
- Political and policy implications of changes in environmental policies (A25): The political and policy implications of changes in environmental policies can be a barrier to the supply chain as changes in environmental policies may create unpredictability and uncertainty in environmental regulations and policies. These changes can lead to changes in legal requirements and obligations, a reduction or increase in financial facilities and taxes, and changes in trade and political relationships. These types of changes can lead to deficiencies and instability in the supply chain.
- Lack of government guarantees and facilities for implementing processes (A26): The lack of government guarantees and facilities can be a barrier to implementing processes and technologies compatible with the environment as the absence of financial guarantees, financial support, and government facilities can reduce the inclination and motivation for investing in green technologies and implementing environmentally friendly processes. This can lead to reduced companies' ability to secure financial resources, delays in the development and implementation of environmental projects, and increased risks in investing in environmental sustainability.
- Need for coordination between government policies and organizations for development (A27): The need for coordination between government policies and organizations can be a barrier to the development of an environmentally sustainable supply chain, as lack of alignment and collaboration between government policies and environmental strategies of organizations can lead to ambiguities and contradictions in procedures and decisions. This need can result in delays in implementing environmental changes, reduced effectiveness of environmental measures, and increased costs.
- Political and policy implications of changes in supply chain strategies on the environment (A28): The political and policy implications of changes in supply chain strategies can be a barrier to environmental protection. Changes in supply chain policies and strategies may lead to changes in legal requirements and obligations, a reduction or increase in financial facilities and taxes, and changes in trade and political relationships. These changes can create unpredictability and uncertainty in environmental

regulations and policies, resulting in insufficient support for environmental conservation and the implementation of environmentally friendly actions.

4. Methodology

4.1. Fuzzy sets theory

The concept of fuzzy sets was introduced by Zadeh [61]. Generally, a fuzzy set is described as a membership function that quantifies the extent to which elements belong to a specific range, typically falling within the [0,1] interval. Triangular fuzzy numbers are preferred over other types of fuzzy numbers in decision-making problems for several reasons [62]. One key benefit is that triangular fuzzy numbers are easier to work with mathematically and computationally compared with other types such as trapezoidal or Gaussian fuzzy numbers. Their simplicity makes them more accessible for decision-makers who may not have a deep understanding of fuzzy set theory. Additionally, triangular fuzzy numbers provide a clear representation of uncertainty and ambiguity in data, as they capture the lower and upper bounds of a fuzzy set along with a modal value. This simplicity and transparency make them well-suited for modeling vague or imprecise information in real-world decision-making scenarios.

Furthermore, triangular fuzzy numbers require only three parameters (the lower bound, upper bound, and modal value) for representation, whereas other types of fuzzy numbers may require additional parameters, leading to increased complexity and computational burden [63]. Overall, the ease of use, clear representation of uncertainty, and simplicity of triangular fuzzy numbers make them a practical choice for decision-making problems where uncertainty and vagueness play a significant role.

The fundamental definitions for fuzzy numerical sets used in this study are outlined below.

Definition 1. A fuzzy set A defined in reference X is in the form of Eq (1):

$$A = \left\{(x, \mu_A(x)) \mid x \in X\right\}. \tag{1}$$

In Eq (1), $\mu_{\tilde{A}}(x): X \to [0,1]$ is the membership function of the set A. The membership value $\mu_A(x)$ indicates the degree of dependence of $x \in X$ in A.

Definition 2. Triangular fuzzy number $\tilde{A}$ is defined as the triple (l, m, u) and the membership function is determined by Eq (2), with its graphical representation depicted in Figure 1.

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x \in (-\infty, l), \\ \dfrac{x-l}{m-l}, & x \in [l, m], \\ \dfrac{u-x}{u-m}, & x \in [m, u], \\ 0, & x \in (u, \infty). \end{cases} \tag{2}$$

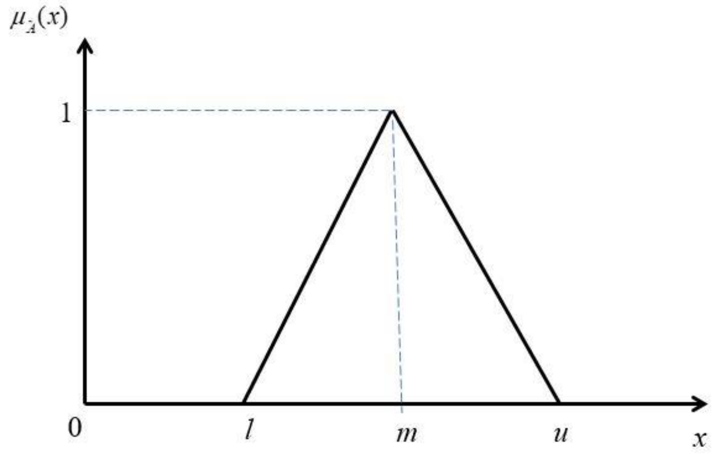

Figure 1. Triangular fuzzy number.

Definition 3. Let us assume that $\tilde{B}=(l_2,m_2,u_2)$, $\tilde{A}=(l_1,m_1,u_1)$ are two equal fuzzy numbers, and λ is a positive constant. In this scenario, arithmetic operations involving these fuzzy numbers are carried out based on Eqs (3)–(7):

$$\tilde{A}\oplus\tilde{B}=(l_1+l_2,m_1+m_2,u_1+u_2)\,, \tag{3}$$

$$\tilde{A}\otimes\tilde{B}=(l_1l_2,m_1m_2,u_1u_2)\,, \tag{4}$$

$$\tilde{A}-\tilde{B}=(l_1-u_2,m_1-m_2,u_1-l_2)\,, \tag{5}$$

$$\tilde{A}/\tilde{B}=(l_1/u_2,m_1/m_2,u_1/l_2)\,, \tag{6}$$

$$\lambda\tilde{A}=\lambda(l_1,m_1,u_1)=(\lambda l_1,\lambda m_1,\lambda u_1)\,. \tag{7}$$

Definition 4. Suppose $\tilde{B}=(l_2,m_2,u_2)$, $\tilde{A}=(l_1,m_1,u_1)$ are two positive triangular fuzzy numbers; the distance between $\tilde{A}$ and $\tilde{B}$ is defined as Eq (8):

$$d(\tilde{A},\tilde{B})=\sqrt{1/3\left((l_1-l_2)^2+(m_1-m_2)^2+(u_1-u_2)^2\right)}. \tag{8}$$

4.2. *Z numbers*

Zadeh introduced the concept of Z numbers [64], which serves as a generalization of uncertainty theory for handling uncertain numerical values. A Z number is composed of a pair of fuzzy numbers, denoted as $Z=(A,B)$, where the first component A represents a fuzzy subset within the domain X, and the second component B represents a fuzzy subset within the unit interval, indicating the degree of reliability of component A. For instance, if we consider failure detection as a Z number, its first component could be "low" while its second component could be "uncertain". A Z valuation is a triplet (X,A,B), which can be seen as a linguistic assignment and is defined as a general constraint on X, as shown in Eq (9):

$$\text{Prob}(X \text{ is } A) \text{ is } B. \tag{9}$$

This limitation is referred to as a probability restriction, which depicts a probability distribution function denoted as *R(x)*. More precisely, it can be defined by Eq (10):

$$R(x): X \text{ is} \rightarrow poss(X = u) = \mu_A(u), \tag{10}$$

where μ_A represents the membership function of *A*, while u represents a generic value of *X*. Moreover, μ_A can be considered as a constraint associated with R(x). This means that $\mu_{(u)}$ covers the degree of satisfiability u. Consequently, *X* can be regarded as a random variable with a probability distribution denoted by *R(x)*, which acts as a probability constraint on X. The probability limit and the probability density function of *X* are as described in Eqs (11) and (12):

$$R(x): X \text{ is } p, \tag{11}$$

$$R(x): X \text{ is } p \rightarrow \text{Prob}(u \leq X \leq u + du) = p(u)du, \tag{12}$$

where du indicates the derivative component of u.

Equation (13) is used to convert the crisp numbers of the reliability values of fuzzy Z numbers:

$$\alpha = \frac{\int x\mu_B dx}{\mu_B dx}. \tag{13}$$

Because of the basic concept behind Z numbers, Zadeh (2011) showed that they are not just components of ordinary pairs. Components A and B are related through a hidden probability and Eq (14) shows this relationship:

$$\sum_{i=1}^{n} \mu_A(x_i) \times p_{xA}(x_i) \rightarrow b_i. \tag{14}$$

To ensure the reliability of the information collected from decision-makers, the data gathered from Z number should be as impartial as possible. To address group decision-making reliability, the number ZE was introduced by Tian et al. [65] with the aim of increasing the number Z.

4.3. ZE numbers

For reliability assurance, the information obtained from decision-makers with the number Z should be as objective as possible. Tian et al. [65] proposed numbers ZE to determine the reliability of group decision-making by improving the numbers Z. The form of numbers ZE is defined by Eq (15):

$$ZE = ((A,R),E). \tag{15}$$

To evaluate the reliability of group decision-making, the voting method was used. According to Eq (16), in this voting approach, Y represents the number of experts who agree with the evaluated Z numbers, N represents the number of experts who disagree, and θ represents the number of experts with neutral opinion:

$$Evaluation - number = (Y, N, \theta). \tag{16}$$

The component E in Eq (17) refers to individual evaluation through group voting to determine the validity of decisions. This indicates the validity of the components A and B. To convert a Z number to a ZE number, you can use Eqs (17) and (18):

$$M = \begin{cases} b_i^* = b_i \times (1+R), & R < 0, \\ b_i^* = b_i, & R = 0, \\ b_i^* = 1-(1-b_i)\times(1-R), & R > 0. \end{cases} \tag{17}$$

$$R = \frac{Y-N}{n-\theta}. \tag{18}$$

The value of b_i^* denotes the adjusted value of b_i, while b_i represents the b_i of the B component in Z numbers, and n represents the total number of participants.

4.4. Fuzzy ZE-SWARA

The method of analysis and evaluation of relative weights (SWARA) was proposed by Stanujkic et al. [66]. Various criteria such as lack of complete information, qualitative judgments of experts, inaccessible information, and uncertainty make decision-making difficult, and common MCDM methods may not be effective in solving significant problems, so decisions are made in a fuzzy environment [43]. The aim of this article is to extend the SWARA method to ZE-SWARA, which is a more powerful approach to problem-solving. A brief description of the ZE-SWARA stages is presented below.

Step 1. Initially, experts rank the criteria in descending order of importance based on their own identification.

Step 2. Based on the initial opinion, experts must assign linguistic variables to the relative importance of criterion *j* compared to the previous *j*−1 criteria.

During this stage, linguistic variables for pairwise comparisons are made based on the TFNs provided in Table 3. The fundamental idea of Z numbers requires combining reliable variables, which are presented in Table 4 for experts to assess their levels of reliability. The mathematical Eq (19) is used to calculate the fuzzy Z value. Additionally, Equation (13) describes the method for determining the value of α. Tables 3 and 4 contain linguistic variables, membership functions, and reliability levels used for evaluating decision-makers' judgments.

$$z\text{-}number(l_{Z(ij)}, m_{Z(ij)}, u_{Z(ij)}) = (l_j \times \sqrt{\alpha} m_j \times \sqrt{\alpha} u_j \times \sqrt{\alpha}). \tag{19}$$

Table 3. Linguistic variables for weight criteria [8].

Linguistic variables	TFNs
Equally important (EI)	(1, 1, 1)
Moderately less important (MOL)	(2/3, 1, 3/2)
Less important (LI)	(2/5, ½, 2/3)
Very less important (VLI)	(2/7, 1/3, 2/5)
Much less important (MUL)	(2/9, ¼, 2/7)

Table 4. Linguistic variables for reliability [9].

Linguistic variables	Very weak (VW)	Weak (W)	Medium (M)	High (H)	Very high (VH)
TFNs	(0,0,0.25)	(0.2,0.35,0.5)	(0.35,0.5,0.75)	(0.5,0.75,0.9)	(0.75,1,1)

The process of comparing the base criterion with other criteria in the Z number method will be done using the pairwise comparison matrix according to Eq (20):

$$\tilde{A}_B = ((l_{Z(B1)}, m_{Z(B1)}, u_{Z(B1)}) \times (l_{Z(B2)}, m_{Z(B2)}, u_{Z(B2)}) \times \ldots \times (l_{Z(Bn)}, m_{Z(Bn)}, u_{Z(Bn)})), \tag{20}$$

In terms of numbers z, $(l_{Z(Bj)}, m_{Z(Bj)}, u_{Z(Bj)})$ indicate the relative importance of the base measure compared to measure j. To determine the relative values indicating the relative importance of criteria in pairwise comparisons, Equation (21) should be used. The use of this equation helps in managing inputs effectively and resolves any inconsistencies.

$$(l_{(ij)}, m_{(ij)}, u_{(ij)}) = \frac{(l_{(Bj)}, m_{(Bj)}, u_{(Bj)})}{(l_{(Bj)}, m_{(Bj)}, u_{(Bj)})}. \tag{21}$$

Step 3. Fuzzy ZE number is generated through experts' preferences in pairwise comparison vectors. In this step, each expert participates in voting for the pairwise comparison preferences of the decision-maker vectors. The fuzzy ZE number is subsequently calculated using Eqs (17) and (18), which define three different states for R. The result of experts' voting determines the state of R, which is then used to calculate new b_i values.

By using updated preferences with ZE fuzzy number concepts, the criteria are sorted in order of priority, from the most favorable to the least favorable as described in Eq (22):

$$(l_{ZE(Bj)}, m_{ZE(Bj)}, u_{ZE(Bj)}) = \begin{cases} ZE = ((l_{B1}, m_{B1}, u_{B1}), (l_R, m_R, u_R), E_1), \\ ZE = ((l_{B2}, m_{B2}, u_{B2}), (l_R, m_R, u_R), E_2), \\ ZE = ((l_{B3}, m_{B3}, u_{B3}), (l_R, m_R, u_R), E_3), \\ \ldots \\ ZE = ((l_{Bn}, m_{Bn}, u_{Bn}), (l_R, m_R, u_R), E_n). \end{cases} \tag{22}$$

Step 4. Based on the results of Step 3, the coefficient $\tilde{q}_j$ is defined as the fuzzy weight coefficient according to Eq (23):

$$q_j = \frac{q_j - 1}{z_j{}'}. \tag{23}$$

Step 5. Finally, considering n evaluation criteria, the relative weight of the jth evaluation criteria is determined as shown in Eq (24):

$$W_j = \frac{q_j}{\sum_{j=1}^{n} q_j}, \tag{24}$$

where $\tilde{w}_j$ is a TFN.

4.5. Fuzzy ZE-MABAC

In this section, we propose the ZE-MABAC method to solve decision-making problems in a fuzzy environment. After obtaining the attribute weights, the standard function value for replacement is calculated using the MABAC method, and the distance of the standard function from the borderline approximation region is defined. After determining the distance of the standard function from the borderline approximation region, the options are ranked, and the best choice is made. We use this method in fuzzy numbers to expand its application domain. The ZE-MABAC method is implemented in the following seven steps.

Step 1. Generate the initial matrix by combining the assessments provided by the decision-makers.

The initial step of any MCDM technique involves the creation of a decision matrix in accordance with Eq (25), the core of which is the evaluation of problem alternatives against criteria. During this stage, decision makers (DMs[1]) assign membership functions based on linguistic variables in Table 5 and reliability linguistic variables based on Table 6 to each element in the decision matrix.

$$Y=\begin{bmatrix} (l_{A11},m_{A11},u_{A11})(l_{R11},m_{R11},u_{R11}) & \cdots & (l_{A1n},m_{A1n},u_{A1n})(l_{R1n},m_{R1n},u_{R1n}) \\ (l_{A21},m_{A21},u_{A21})(l_{R21},m_{R21},u_{R21}) & \cdots & (l_{A2n},m_{A2n},u_{A2n})(l_{R2n},m_{R2n},u_{R2n}) \\ \vdots & \ddots & \vdots \\ (l_{Am1},m_{Am1},u_{Am1})(l_{Rm1},m_{Rm1},u_{Rm1}) & \cdots & (l_{Amn},m_{Amn},u_{Amn})(l_{Rmn},m_{Rmn},u_{Rmn}) \end{bmatrix}. \quad (25)$$

Table 5. Verbal variables of barriers modes.

Verbal variables	TFNs
Extremely poor (EP)	(0,0,1)
Poor (P)	(0,1,3)
Medium poor (MP)	(1,3,5)
Medium (M)	(3,5,7)
Medium great (MG)	(5,7,9)
Great (G)	(7,9,10)
Extremely great (EG)	(9,10,10)

Table 6. Linguistic variables for reliability [19].

Linguistic variables	Very weak (VW)	Weak (W)	Medium (M)	High (H)	Very high (VH)
TFNs	(0,0,0.25)	(0.2,0.35,0.5)	(0.35,0.5,0.75)	(0.5,0.75,0.9)	(0.75,1,1)

The component Y represents the decision matrix considering m alternatives $\{A_1,A_2,...,A_m\}$ and n criteria $\{C_1,C_2,...,C_n\}$. The initial matrix is composed of TFNs that represent both the membership function $(l_{Aij},m_{Aij},u_{Aij})$ and the certainty function $(l_{Rij},m_{Rij},u_{Rij})$.

Step 2. Collecting expert opinions for each alternative row to calculate fuzzy ZE numbers.

In this step, experts provide their opinions for each existing alternative row. The decision matrix of fuzzy ZE numbers (26) is derived from expert opinions and is represented in Eq (26):

$$Y_{ZE}=\begin{bmatrix} (l_{ZE(11)},m_{ZE(11)},u_{ZE(11)}) & (l_{ZE(12)},m_{ZE(12)},u_{ZE(12)}) & \cdots & (l_{ZE(1n)},m_{ZE(1n)},u_{ZE(1n)}) \\ (l_{ZE(21)},m_{ZE(21)},u_{ZE(21)}) & (l_{ZE(22)},m_{ZE(22)},u_{ZE(22)}) & \cdots & (l_{ZE(2n)},m_{ZE(2n)},u_{ZE(2n)}) \\ \vdots & \vdots & \ddots & \vdots \\ (l_{ZE(m1)},m_{ZE(m1)},u_{ZE(m1)}) & (l_{ZE(m2)},m_{ZE(m2)},u_{ZE(m2)}) & \cdots & (l_{ZE(mn)},m_{ZE(mn)},u_{ZE(mn)}) \end{bmatrix}. \quad (26)$$

Step 3. Normalizing the decision matrix of fuzzy ZE numbers.

The fuzzy decision matrix is normalized to enhance its comparability, and the first instance of this method is employed in fuzzy TOPSIS, leading to increased efficiency and accuracy in numerical evaluation.

Equations (27)–(29) show how to normalize fuzzy ZE numbers for components i and j for $\tilde{N}_{ij} = (n^l_{ZE(ij)}, n^m_{ZE(ij)}, n^u_{ZE(ij)})$, we have:

$$n^l_{ZE(ij)} = \frac{l_{ZE(ij)}}{\sqrt{\sum_{i=1}^{m}\left[(l_{ZE(ij)})^2 + (m_{ZE(ij)})^2 + (u_{ZE(ij)})^2\right]}}, \tag{27}$$

$$n^m_{ZE(ij)} = \frac{m_{ZE(ij)}}{\sqrt{\sum_{i=1}^{m}\left[(l_{ZE(ij)})^2 + (m_{ZE(ij)})^2 + (u_{ZE(ij)})^2\right]}}, \tag{28}$$

$$n^u_{ZE(ij)} = \frac{u_{ZE(ij)}}{\sqrt{\sum_{i=1}^{m}\left[(l_{ZE(ij)})^2 + (m_{ZE(ij)})^2 + (u_{ZE(ij)})^2\right]}}. \tag{29}$$

Step 4. Calculating the normalized weighted decision matrix using the ZE-SWARA method to compute the normalized weighted values.

Step 5. Determine the approximate boundary region matrix $\tilde{G}$. Calculate the boundary region area of each standard according to Eqs (30) and (31):

$$\tilde{g}_j = \left(\prod_{i=1}^{m} \tilde{r}_{ij}\right)^{1/m}, \tag{30}$$

$$\tilde{G} = \left(\tilde{g}_1, \tilde{g}_2, \ldots.., \tilde{g}_n\right). \tag{31}$$

Step 6. Calculate the distance between the alternative option and the approximate boundary region for the elements of the matrix based on Eq (32):

$$\tilde{Q} = \begin{pmatrix} \tilde{q}_{11} & \cdots & \tilde{q}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{q}_{m1} & \cdots & \tilde{q}_{mn} \end{pmatrix}. \tag{32}$$

The element present in matrix $\tilde{Q}$ is obtained by finding the distance between the weighted matrix $\tilde{R}$ and the approximate boundary region matrix $\tilde{G}$, as shown in Eq (33):

$$\tilde{Q} = \tilde{R} - \tilde{G} = \begin{pmatrix} \tilde{r}_{11} & \cdots & \tilde{r}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{r}_{m1} & \cdots & \tilde{r}_{mn} \end{pmatrix} - \begin{pmatrix} \tilde{q}_{1} & \cdots & \tilde{q}_{n} \\ \vdots & \ddots & \vdots \\ \tilde{q}_{1} & \cdots & \tilde{q}_{n} \end{pmatrix}, \tag{33}$$

When $q_{ij} > 0$, the i_{th} alternative under the j_{th} criterion is located in the upper approximate region (G^+), which is a more ideal selection region. When $q_{ij} < 0$, the i-th alternative under the j_{th} criterion is in a lower approximate region (G^-), which is a less ideal region. Therefore, to select the i_{th}alternative as the best solution, more criteria should be located in the upper approximate region.

Step 7. Ranking the alternatives. First, the replacement distances for each alternative under all criteria are summed to obtain $\tilde{S}_i$, and then $\tilde{S}_i$is defuzzified to obtain a clear number. Sorting the alternatives based on the size of S_i yields the final result as shown in Eq (34):

$$\tilde{S}_i = \sum_{j=1}^{n} \tilde{g}_{ij}, \qquad \text{i} = 1, 2, \ldots \text{m}. \tag{34}$$

5. Experimental results

This section provides a comprehensive explanation of the execution of the method, including the results of the analysis of weighting coefficients and the ranking of alternatives within the proposed framework. We present the weighting coefficient findings based on ZE-SWARA and the ranking results using ZE-MABAC.

5.1. Weight criteria

The goal of this section is to demonstrate the results of the weighting coefficient analysis using SWARA within the ZE fuzzy framework. Following the SWARA framework, after determining the most desirable and least desirable criteria by the expert group, pairwise comparisons between criteria are made using linguistic variables. Values are assigned based on membership functions and reliability, as mentioned in Tables 3 and 4. After presenting their judgments, 12 experts in this field provide their opinions on each decision. In this stage, if an expert agrees with the decision-maker's opinion, they vote "Yes". If they disagree, they vote "No", and if they are undecided, they vote "θ". The evaluation results of DMS and expert judgments for the criteria are shown in Table 7.

Table 7. Results of DMS evaluations and experts' judgments for eco-regenerative supply chains criteria.

			y	n	θ	R
DM1	O					
	C	MOL-H	8	1	3	0.777778
	S	LI-VH	6	2	4	0.5
	D	MUL-VH	7	4	1	0.272727
	T	VLI-M	6	4	2	0.2
DM2	C					
	S	LI-VH	5	2	5	0.428571
	D	MOL-H	4	6	2	-0.2
	O	VLI-M	8	2	2	0.6
	T	MUL-VH	7	4	1	0.272727
DM3	S					
	C	MOL-H	5	3	4	0.25
	D	VLI-M	4	2	6	0.333333
	T	VLI-H	7	2	3	0.555556
	O	MUL-VH	9	0	3	1

In the next step, ZE values for criteria and sub-criteria are calculated, and then the final fuzzy weights for criteria obtained through the application of ZE-SWARA are determined. Table 8 displays the calculated final fuzzy weights. Based on the weighting values obtained from the ZE-SWARA method in the table, it can be concluded that the cost criterion has the highest weighting coefficient.

Table 8. The final weight of criteria with Fuzzy ZE-SWARA method.

DM1					K			q			Wj			Y	N	θ	R
O					1	1	1	1.000	1.000	1.000	0.3771	0.4348	0.5102				
C	MOL-H	0.647	0.970	1.455	1.6466	1.9699	2.4549	0.407	0.508	0.607	0.1536	0.2207	0.3099	8	1	3	0.77778
S	LI-VH	0.396	0.495	0.660	1.3958	1.4948	1.6597	0.245	0.340	0.435	0.0925	0.1477	0.2220	6	2	4	0.50000
D	MULVH	0.219	0.246	0.281	1.2188	1.2462	1.2814	0.192	0.273	0.357	0.0722	0.1185	0.1821	7	4	1	0.27273
T	VLI-M	0.224	0.261	0.313	1.2238	1.2611	1.3133	0.146	0.216	0.292	0.0550	0.0940	0.1488	6	4	2	0.20000
							sum	1.990	2.336	2.691							
DM2					K			q			Wj						
C					1	1	1	1.000	1.000	1.000	0.3638	0.4082	0.4662				
S	LI-VH	0.395	0.494	0.659	1.3952	1.4940	1.6587	0.603	0.669	0.717	0.2193	0.2732	0.3341	5	2	5	0.42857
D	MOL-H	0.511	0.766	1.149	1.5106	1.7659	2.1489	0.281	0.379	0.474	0.1021	0.1547	0.2212	4	6	2	–0.20000
O	VLI-M	0.257	0.299	0.359	1.2566	1.2994	1.3593	0.206	0.292	0.378	0.0751	0.1191	0.1760	8	2	2	0.60000
T	MUL-VH	0.219	0.246	0.281	1.2188	1.2462	1.2814	0.161	0.234	0.310	0.0586	0.0955	0.1444	7	4	1	0.27273
							sum	2.251	2.574	2.879							
DM3					K			q			Wj						
S					1	1	1	1.000	1.000	1.000	0.3667	0.4200	0.4880				
C	MOL-H	0.596	0.894	1.342	1.5963	1.8944	2.3416	0.427	0.528	0.626	0.1566	0.2217	0.3057	5	3	4	0.25000
D	VLI-M	0.235	0.274	0.329	1.2352	1.2744	1.3293	0.321	0.414	0.507	0.1178	0.1740	0.2475	4	2	6	0.33333
T	VLI-H	0.268	0.313	0.376	1.2682	1.3130	1.3755	0.234	0.315	0.400	0.0856	0.1325	0.1952	7	2	3	0.55556
O	MUL-VH	0.222	0.250	0.286	1.2222	1.2500	1.2857	0.182	0.252	0.327	0.0666	0.1060	0.1597	9	0	3	1.00000
							sum	2.164	2.510	2.861							

5.2. Strategies ranking

In this section, the results of ranking different strategic options using input data from decision-makers and experts are presented. Following the steps of the ZE-MABAC method for ranking these options, decision-makers first express their opinions in the fuzzy decision matrix using linguistic membership functions as mentioned in Table 5. Then, in the second step, domain experts provide their judgments on the decisions made by the decision-makers. The results of steps one and two for 28 obstacles and 5 criteria available for the first, second, and third decision-makers are presented in Tables 9–13. Here, component "A" refers to the value of the membership function, and component "B" represents the reliability value.

Table 9. Decision matrix formed by DM1.

	S		O		D		C		T		Expert opinions			R
Barriers	A	B	A	B	A	B	A	B	A	B	Y	N	θ	
A1	MG	H	G	VH	G	VH	G	H	MP	VH	8	2	2	0.6
A2	MG	M	G	H	VG	H	G	VH	G	VH	8	3	1	0.4545
A3	F	H	MG	M	G	M	G	M	MP	M	6	5	1	0.0909
A4	F	H	P	H	MG	H	VP	H	VP	M	1	8	3	–0.7777
A5	MG	H	F	M	MG	M	P	H	MG	M	4	4	4	0
A6	F	H	MG	M	P	M	G	VW	F	H	3	6	3	–0.3333
A7	F	M	G	H	MG	H	F	H	MP	H	6	4	2	0.2
A8	F	H	MG	M	MG	M	MG	H	P	W	4	7	1	–0.2727
A9	MG	VH	MG	M	F	M	F	M	MP	W	9	1	2	0.8
A10	MG	H	F	W	MP	W	MG	W	F	M	6	4	2	0.2
A11	F	H	MP	W	MP	W	P	H	MP	M	3	8	1	–0.4545
A12	G	H	F	W	MG	W	MG	M	MP	W	7	2	3	0.5555
A13	G	M	G	VW	F	VW	MP	W	P	H	5	5	2	0
A14	F	VW	MP	H	VP	H	F	M	P	W	2	10	0	–0.666
A15	MG	VH	F	H	G	H	MG	M	P	VW	4	6	2	–0.2
A16	G	M	MG	M	MP	M	G	VH	MP	M	4	4	4	0
A17	F	M	MG	W	MP	W	F	VH	F	M	6	2	4	0.5
A18	F	M	MP	H	MG	H	MG	H	MP	M	4	5	3	–0.111
A19	MG	H	G	VH	G	VH	F	H	F	H	4	3	5	0.1428
A20	G	VH	G	H	MG	H	G	VW	P	W	5	3	4	0.25
A21	MG	VH	VG	H	P	H	F	M	P	M	5	6	1	–0.0909
A22	MG	H	F	M	MP	M	MP	H	P	H	3	8	1	–0.454
A23	MG	H	MG	M	G	M	F	H	F	H	9	2	1	0.6363
A24	MG	W	F	H	MP	H	MP	W	P	VH	2	8	2	–0.6
A25	MG	W	MG	H	MP	H	F	M	F	M	3	7	2	–0.4
A26	MG	H	MG	H	MG	H	G	M	P	M	7	4	1	0.2727
A27	VG	VH	MG	W	MP	W	MG	W	F	H	4	3	5	0.1428
A28	MG	VH	MG	H	F	H	MP	H	P	M	2	10	0	–0.666

Table 10. Decision matrix formed by DM2.

	S		O		D		C		T		Expert opinions			R
											Y	N	θ	
Barriers	A	B	A	B	A	B	A	B	A	B				
A1	G	VH	MG	H	F	M	G	H	P	VH	8	3	1	0.45454
A2	MG	H	MG	H	G	H	MG	M	F	M	9	1	2	0.8
A3	G	VH	MG	H	F	H	G	M	VP	VW	6	5	1	0.09090
A4	MP	M	F	M	MP	W	F	VH	VP	W	2	7	3	–0.55556
A5	MG	VH	MG	M	F	H	MP	VW	F	H	4	4	4	0
A6	MP	M	G	VW	MP	H	MG	M	MP	M	3	6	3	–0.33333
A7	MG	H	G	M	MP	M	MG	M	MP	VH	6	4	2	0.2
A8	F	M	F	VH	F	H	F	H	F	M	4	6	2	–0.2
A9	G	H	G	H	F	W	G	VH	MG	VH	10	1	1	0.818182
A10	MG	W	MG	W	F	M	G	H	MP	H	6	4	2	0.2
A11	G	M	F	H	MG	H	F	M	MP	VH	4	6	2	–0.2
A12	MG	H	MG	W	G	M	G	H	F	M	7	2	3	0.555556
A13	MG	W	G	H	F	VH	MG	H	F	VH	4	6	2	–0.2
A14	MP	H	P	W	P	H	MG	M	P	H	2	10	0	–0.66667
A15	F	W	MG	H	G	M	F	H	P	VH	4	6	2	–0.2
A16	MP	H	F	W	MP	H	MG	M	P	VW	4	4	4	0
A17	G	M	G	H	MP	M	MG	H	MG	H	5	3	4	0.25
A18	G	H	F	H	G	W	F	H	F	H	4	5	3	–0.11111
A19	MG	H	MP	H	MG	H	MG	M	MP	H	5	4	3	0.111111
A20	G	W	MG	H	MG	M	MG	M	P	M	6	4	2	0.2
A21	G	M	G	H	MP	H	MG	M	MP	W	5	6	1	–0.09091
A22	MP	VH	MG	H	MP	H	MP	VH	VP	H	3	8	1	–0.45455
A23	G	VH	F	M	MG	H	MG	M	P	H	8	3	1	0.454545
A24	MG	H	MG	W	P	W	MG	H	P	W	2	8	2	–0.6
A25	MP	H	G	VH	P	H	MP	W	MP	H	3	7	2	–0.4
A26	G	VH	G	H	MP	M	G	H	MP	H	9	2	1	0.636364
A27	G	M	G	M	MG	H	MP	VH	MP	W	4	3	5	0.142857
A28	MG	H	G	H	F	M	P	W	P	H	2	10	0	–0.66667

Table 11. Decision matrix formed by DM3.

	S		O		D		C		T		Expert opinions			R
											Y	N	θ	
Barriers	A	B	A	B	A	B	A	B	A	B				
A1	VG	M	MG	H	MP	W	F	H	MP	H	7	2	3	0.555556
A2	F	H	MG	VH	G	H	F	H	MP	H	8	1	3	0.777778
A3	MG	H	F	H	F	VH	MG	M	VP	W	6	5	1	0.090909
A4	P	M	MP	H	F	M	F	H	VP	W	2	7	3	–0.55556
A5	F	H	G	H	F	M	F	M	P	H	3	4	5	–0.14286
A6	MP	W	MG	H	VP	W	G	H	MP	H	3	6	3	–0.33333
A7	G	M	MG	VH	F	H	F	M	F	M	5	5	2	0
A8	MP	H	MP	W	F	W	G	W	MP	H	5	6	1	–0.09091
A9	MG	H	VG	H	G	M	MG	VH	F	VH	10	1	1	0.818182
A10	MG	H	F	H	MP	M	G	M	MP	M	5	4	3	0.111111
A11	MG	W	MG	H	F	W	P	W	F	H	4	6	2	–0.2
A12	G	VH	F	M	MP	W	MG	VH	MP	M	5	3	4	0.25
A13	MG	H	MG	W	F	H	F	VH	MP	VH	4	6	2	–0.2
A14	MG	M	F	H	P	M	F	H	MP	W	1	11	0	–0.83333
A15	F	H	G	M	MG	VW	MP	W	MP	H	4	6	2	–0.2
A16	F	M	F	W	F	W	G	H	VP	W	5	4	0	0.111111
A17	F	H	G	VH	P	VH	G	H	MG	W	5	3	4	0.25
A18	MG	W	F	VH	MG	M	MG	M	F	W	4	5	3	–0.11111
A19	G	W	F	M	F	M	MP	H	MP	W	5	4	3	0.111111
A20	MG	M	F	M	MG	H	MG	H	MP	H	5	4	3	0.111111
A21	F	VW	MG	W	P	VW	MG	M	MP	M	5	6	1	–0.09091
A22	F	H	MG	H	P	W	F	W	P	VW	2	7	3	–0.55556
A23	G	VH	F	VW	G	VH	MG	H	MP	M	8	4	0	0.333333
A24	F	H	MP	M	MP	H	F	VW	P	VH	2	8	2	–0.6
A25	MG	VH	MG	H	MP	W	MP	H	P	H	3	7	2	–0.4
A26	VG	VH	G	H	G	H	MG	W	F	VH	10	1	1	0.818182
A27	G	H	F	M	G	VH	G	W	P	VH	4	3	5	0.142857
A28	F	H	MG	VH	F	H	VP	H	P	W	2	10	0	–0.66667

Table 12. Group fuzzy ZE numbers decision matrix.

Barriers	S			O			D			C			T		
A1	6.2449	7.3424	8.4398	5.4193	6.6815	7.9437	4.0201	5.0584	6.0966	5.6142	6.5503	7.4865	1.6165	2.9113	4.2061
A2	4.3450	5.5839	6.8227	5.4375	6.7298	8.0221	6.9985	7.9543	8.9100	5.1840	6.3120	7.4401	4.2205	5.3518	6.4831
A3	4.8999	5.9522	7.0044	3.8591	4.9588	6.0584	4.2154	5.0821	5.9487	4.7420	5.6155	6.4890	0.4992	1.2063	1.9135
A4	1.0174	1.5513	2.0852	1.1541	1.7338	2.3136	1.5747	2.1335	2.6922	1.6314	2.1738	2.7162	0.0000	0.3759	0.7518
A5	4.1159	5.2978	6.4798	4.0063	4.8696	5.7329	3.2271	4.0938	4.9604	1.3088	1.9182	2.5275	2.6041	3.5132	4.4223
A6	1.6456	2.4136	3.1816	2.5324	3.2310	3.9296	0.6618	1.3680	2.0743	2.9985	3.5806	4.1627	1.7897	2.6658	3.5419
A7	4.1996	5.1438	6.0879	5.5285	6.5746	7.6208	3.1421	4.2626	5.3831	3.4462	4.3731	5.2999	2.2051	3.3798	4.5545
A8	2.3753	3.2413	4.1072	2.5652	3.4456	4.3260	2.7950	3.5448	4.2947	3.5546	4.3631	5.1716	1.5697	2.3604	3.1512
A9	5.5615	6.8723	8.1831	6.4613	7.5869	8.7124	4.7478	5.6960	6.6441	5.2521	6.3991	7.5460	3.6104	4.9070	6.2035
A10	4.0887	5.3154	6.5420	3.2431	4.1116	4.9801	2.0096	2.9947	3.9797	4.9864	5.8802	6.7740	2.1390	3.2211	4.3033
A11	3.2253	3.9150	4.6047	2.5891	3.4459	4.3026	2.2734	3.0512	3.8290	1.2444	1.8459	2.4474	1.9589	2.9174	3.8760
A12	6.0521	7.1626	8.2730	3.5944	4.5633	5.5322	3.9503	5.0253	6.1002	5.3080	6.5561	7.8042	2.2759	3.3922	4.5084
A13	3.8357	4.7228	5.6100	3.1454	3.7333	4.3213	2.4609	3.0761	3.6913	2.8384	3.8091	4.7797	2.0366	3.0518	4.0669
A14	0.9758	1.4090	1.8422	0.9096	1.3872	1.8648	0.2626	0.6900	1.1175	1.7111	2.1735	2.6359	0.4397	0.8391	1.2385
A15	3.1861	4.0556	4.9251	3.7979	4.6505	5.5031	3.5916	4.1525	4.7134	2.4455	3.2869	4.1282	0.8634	1.5990	2.3347
A16	3.2551	4.1746	5.0941	2.8532	3.6264	4.3996	1.9165	2.9206	3.9248	5.5203	6.4972	7.4741	0.5472	1.1913	1.8353
A17	4.2167	5.0712	5.9258	5.7529	6.7899	7.8269	1.4081	2.5462	3.6843	4.8971	5.9723	7.0475	3.8450	4.9404	6.0358
A18	3.7171	4.4910	5.2649	2.8454	3.8258	4.8063	3.7766	4.7050	5.6335	3.5516	4.5633	5.5749	2.2720	3.0659	3.8598
A19	4.4358	5.5283	6.6208	3.8806	4.8964	5.9122	4.7541	5.7699	6.7857	3.0121	4.1192	5.2264	2.1866	3.2410	4.2954
A20	5.1719	6.1085	7.0452	4.5722	5.5656	6.5589	4.2518	5.5273	6.8028	3.9985	5.0036	6.0087	1.0820	2.0184	2.9548
A21	3.4143	4.1743	4.9343	5.0226	5.8490	6.6753	0.8814	1.6267	2.3719	3.1983	4.1121	5.0259	1.0614	1.9146	2.7677
A22	2.2973	3.1653	4.0333	2.7134	3.4920	4.2707	0.9070	1.6201	2.3333	1.4295	2.2387	3.0479	0.2562	0.7232	1.1902
A23	6.1912	7.3245	8.4578	3.4585	4.3988	5.3391	5.9598	7.0533	8.1468	4.2085	5.4077	6.6069	2.1240	3.1606	4.1971
A24	2.2484	2.8868	3.5253	1.6488	2.2437	2.8387	0.8469	1.5132	2.1795	1.3242	1.8252	2.3261	0.5375	1.0750	1.6124
A25	2.4698	3.4097	4.3497	3.9804	4.8965	5.8126	0.9688	1.7507	2.5326	1.4901	2.2365	2.9829	1.4057	2.1441	2.8824
A26	6.4685	7.5803	8.6920	5.9897	7.0805	8.1714	4.3777	5.6057	6.8337	5.6614	6.7161	7.7708	2.2302	3.3059	4.3815
A27	6.4538	7.3290	8.2042	3.9153	4.7582	5.6012	4.1988	5.2980	6.3972	3.3166	4.3621	5.4077	1.9421	2.8949	3.8477
A28	2.4252	3.1198	3.8144	2.9196	3.6143	4.3089	1.8718	2.3397	2.8076	0.4435	0.9693	1.4952	0.4170	0.8340	1.2510

Table 13. The final ranks of the barriers.

Barriers	Si			Defuzzification of Si	Defuzzification of Si	Ranking
A1	–0.8916	0.2845	1.4984	0.2971	0.2971	4
A2	–0.8998	0.3031	1.5538	0.3190	0.3190	3
A3	–1.0015	0.1216	1.2554	0.1252	0.1252	10
A4	–1.3050	–0.3263	0.6024	–0.3430	–0.3430	27
A5	–1.1155	–0.0260	1.0641	–0.0258	–0.0258	16
A6	–1.2063	–0.1739	0.8357	–0.1815	–0.1815	23
A7	–1.0191	0.1118	1.2644	0.1190	0.1190	11
A8	–1.1454	–0.0752	0.9871	–0.0778	–0.0778	20
A9	–0.8710	0.3311	1.5814	0.3472	0.3472	1
A10	–1.0395	0.0821	1.2201	0.0876	0.0876	13
A11	–1.1923	–0.1469	0.8818	–0.1525	–0.1525	22
A12	–0.9411	0.2258	1.4270	0.2372	0.2372	5
A13	–1.1106	–0.0312	1.0434	–0.0328	–0.0328	18
A14	–1.3195	–0.3585	0.5440	–0.3780	–0.3780	28
A15	–1.1264	–0.0552	1.0054	–0.0587	–0.0587	19
A16	–1.0736	0.0159	1.1048	0.0157	0.0157	15
A17	–0.9721	0.1730	1.3447	0.1819	0.1819	7
A18	–1.0817	0.0203	1.1278	0.0222	0.0222	14
A19	–1.0440	0.0923	1.2517	0.1000	0.1000	12
A20	–0.9940	0.1419	1.2993	0.1491	0.1491	9
A21	–1.0981	–0.0237	1.0443	–0.0258	–0.0258	17
A22	–1.2440	–0.2187	0.7793	–0.2278	–0.2278	24
A23	–0.9525	0.2140	1.4132	0.2249	0.2249	6
A24	–1.2700	–0.2760	0.6760	–0.2900	–0.2900	26
A25	–1.1965	–0.1446	0.8936	–0.1492	–0.1492	21
A26	–0.8606	0.3267	1.5548	0.3403	0.3403	2
A27	–0.9836	0.1493	1.2998	0.1552	0.1552	8
A28	–1.2532	–0.2516	0.7082	–0.2656	–0.2656	25

Based on the evaluation of obstacles to implementing environmentally sustainable supply chains, defining a set of criteria for assessing these obstacles, and proposing strategies for improving the implementation of environmentally sustainable supply chains, considering the results of the ZE-MABAC ranking method, the lack of awareness and knowledge about environmentally friendly technologies in society and organizations (A9) ranks first. In second and third place, the lack of guarantees and government facilities for implementing processes and technologies (A26) and the high costs of developing and implementing processes and technologies (A2) are positioned. Finally, the need for coordination and collaboration among supply chain members for the implementation of processes and technologies (A14) is of the least importance among the obstacles.

The aim of this section is to compare the ranking of obstacles using various MCDM methods. Based on the evaluation of obstacles to implementing environmentally sustainable supply chains, defining a set of criteria for assessing these obstacles, and proposing strategies for improving the implementation of environmentally sustainable supply chains, according to the results of the ZE-MABAC ranking method (Table 14), in regular FMEA, the A2 is the highest among the other items (with RPN = 31752) and holds the first rank, considered the most significant obstacle. A9, with RPN = 24192, ranks second, and A26 and A1, with RPN = 21952, are in third place. The fundamental problem of regular FMEA is ranking A26 and A1 as the third priority. This uncertainty in FMEA indicates complexity and confusion that may arise in the decision-making process. It is evident that in the area of the supply chain related to environmental health, the results should be precise and distinct.

Table 14. Comparison of rankings obtained from four methods.

Barriers	ZE-MABAC	RANK	Z-MABAC	RANK	FUZZY-MABAC	RANK	RPN	RANK
A1	0.297087325	4	0.231284811	4	0.150462	3	21952	3
A2	0.319020859	3	0.232195686	3	0.138821	4	31752	1
A3	0.125163957	10	0.105590669	8	0.056876	13	8960	7
A4	–0.342957241	27	–0.26623204	28	–0.29907	28	72	28
A5	–0.025804188	16	–0.03618812	19	–0.049	21	1200	23
A6	–0.181475179	23	–0.130589393	24	–0.02527	20	3780	13
A7	0.118994054	11	0.089217647	10	0.063254	10	4900	11
A8	–0.077820612	20	–0.053944227	21	–0.02014	19	3780	13
A9	0.347184721	1	0.237081053	2	0.160992	2	24192	2
A10	0.087597569	13	0.00774666	14	0.058402	11	3675	16
A11	–0.152502651	22	–0.125360705	23	–0.11049	23	1800	20
A12	0.23724773	5	0.119661551	6	0.112176	7	8064	8
A13	–0.032800181	18	0.000989953	15	0.057886	12	3360	18
A14	–0.377968032	28	–0.241799861	27	–0.20317	27	256	27
A15	–0.058735089	19	–0.022247864	17	–0.00815	17	8064	8
A16	0.01569104	15	–0.035378265	18	–0.00982	18	3528	17
A17	0.18187425	7	0.106386432	7	0.073772	9	3780	13
A18	0.02215076	14	0.028517909	13	0.024765	16	1800	20
A19	0.100010526	12	0.033832844	12	0.026084	15	4200	12
A20	0.149085086	9	0.060559976	11	0.13221	6	12544	5
A21	–0.025814772	17	–0.019898693	16	0.038167	14	2835	19
A22	–0.227803538	24	–0.135283896	25	–0.16498	26	720	25
A23	0.224895199	6	0.124343163	5	0.091368	8	5040	10
A24	–0.289992884	26	–0.170410609	26	–0.1151	24	600	26
A25	–0.149166654	21	–0.051872831	20	–0.08565	22	1080	24
A26	0.340294504	2	0.269277472	1	0.200391	1	21952	3
A27	0.15519027	8	0.094115579	9	0.132639	5	10080	6
A28	–0.265556981	25	–0.066932515	22	–0.12532	25	1728	22

According to the FUZZY-MABAC report, the ranking changes as follows: A26 is in the first place, and A9, A1, and A2 are in the second, third, and fourth ranks, respectively. Although the results using FUZZY-MABAC change due to uncertainty in the weighting process (SODCT), the reliability of expert opinions has not yet been considered. The reliability of data plays a crucial role in MCDM issues, as expert opinions are fundamental for decision-making. Therefore, considering reliability can provide validation for achieving more accurate results. Based on this, the Z-MABAC method was used for better decision-making regarding reducing obstacles in the environmentally sustainable supply chain process. The results of the Z-MABAC method are as follows: A26 ranks first, and A9, A2, and A1 are in the second, third, and fourth ranks, respectively. Additionally, for objective reliability, the information obtained from decision-makers' Z numbers should be as objective as possible. For this reason, ZE numbers were used to determine the reliability of group decision-making with improved Z numbers in this article. The results of the ZE-MABAC method are as follows: A9 is the first priority, and A26, A2, and A1 are in the second, third, and fourth ranks, respectively. The ZE-MABAC method assigns the top rank to A9, while it is in the second rank in the Z-MABAC approach.

5.3. Sensitivity analysis

After obtaining the initial results in the MCMD model, the question arises as to how the subjectively defined input parameters affect the results of the model and what results are obtained by applying other multi-criteria models. Therefore, an essential step in multi-criteria decision-making is to check the conformity of the results and analyze the sensitivity of the results to changes in the input parameters of the MCDM model. This section performs the sensitivity analysis to show the reliability of the outputs for the criteria under review. The weights of the criteria have a significant effect on the ranking of barriers, and their change affects the final results. Changing weights is crucial for a more accurate understanding of the importance of criteria in evaluating green supply chain barriers. Remarkably, even slight changes in the weights assigned to the criteria can lead to significant changes in the final ranking of obstacles. To achieve this goal, a sensitivity analysis is performed by manipulating the weights assigned to the different criteria, thereby determining the ranking of the options. It is very important to understand the ranking results using the fuzzy ZE-MABAC method. The weights of the decision makers' coefficients were defined based on subjective evaluations and were used to integrate the weights of the criteria's coefficients; sensitivity analysis was performed in 3 modes and 11 scenarios. First, the ranking of these barriers is established by assuming the same weights are applied to all criteria. This involves dividing the value of 1 by the total of 5 criteria and creating the weight of the corresponding criteria. Two other cases indicate that (a) "only" the effect of a primary criterion is considered and (b) the effect of removing a criterion is considered. These visual representations serve as a powerful tool to gain insight into the robustness and sensitivity of the ranking results, ultimately helping to make informed barrier selection. Figure 2 emphasizes the differences in the ranking of barriers that arose when using different scenarios for all criteria.

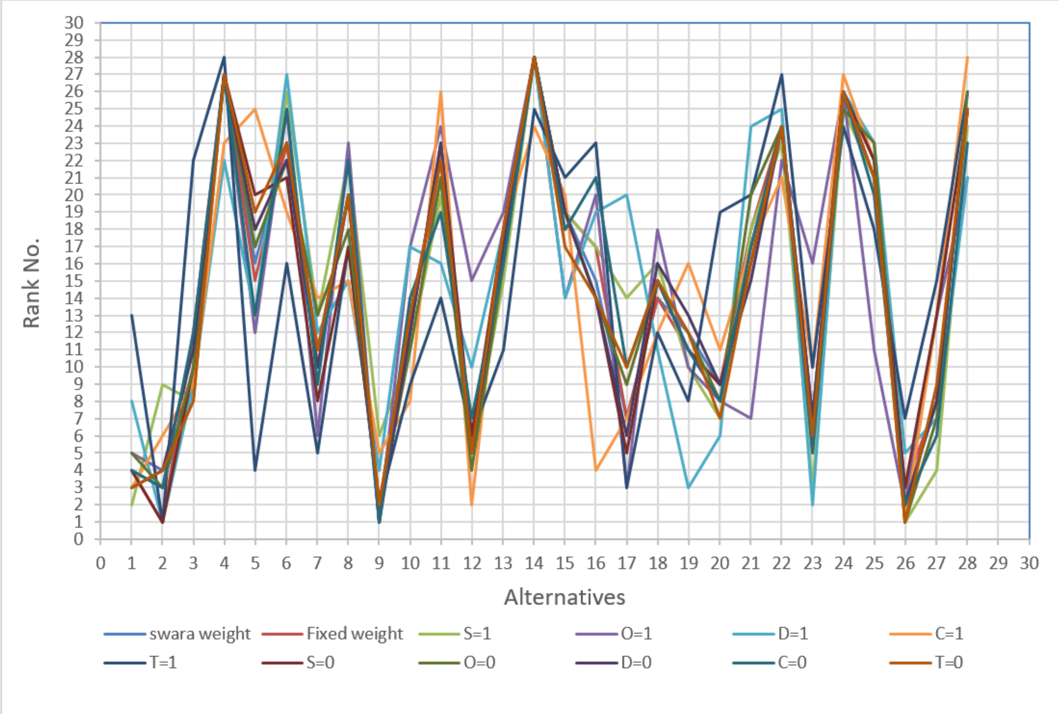

Figure 2. Changes in alternative assessment scores caused by various scenarios.

After conducting an analysis of various sensitivities and examining their outcomes, as depicted in Table 15, it is evident that the ranking of the options experiences several fluctuations. Nevertheless, options A2, A9, and A26 consistently maintain top positions across different sensitivities within the scenario. These options yield diverse results, underscoring the significance of subjective assessments carried out by DMs. Such evaluations serve as a crucial factor in determining the most optimal and effective option in MCDM processes, thereby playing a pivotal role in shaping policy decisions within this domain.

The results of the analysis highlight the critical role of subjective evaluations in the decision-making process. DMs rely on their expertise, experience, and judgment to assess the various options and prioritize them based on their perceived effectiveness and suitability. In the context of MCDM, where multiple factors need to be considered, subjective evaluations provide valuable insights that quantitative data alone may not capture.

In conclusion, the analysis of different sensitivities and their impact on the ranking of options underscores the importance of subjective evaluations in MCDM processes. By leveraging the insights and expertise of DMs, organizations and policymakers can identify the most optimal and effective options that align with their goals and objectives.

Table 15. Ranking of the alternatives based on various scenarios.

Alternative	SWARA weight	Fixed weight	S=1	O=1	D=1	C=1	T=1	S=0	O=0	D=0	C=0	T=0
A1	4	4	2	5	8	3	13	4	5	3	4	3
A2	3	1	9	4	1	6	1	1	3	4	3	4
A3	10	12	8	9	9	9	22	10	10	11	12	8
A4	27	27	27	27	22	23	28	27	27	27	27	27
A5	16	15	12	12	13	25	4	20	17	18	13	19
A6	23	23	26	25	27	19	16	21	22	22	25	23
A7	11	10	13	6	12	14	5	8	13	10	9	11
A8	20	20	22	23	15	15	17	17	18	20	22	20
A9	1	2	6	1	4	5	2	2	2	1	1	2
A10	13	13	11	17	17	8	9	12	11	12	14	13
A11	22	21	20	24	16	26	14	23	21	23	19	22
A12	5	6	5	15	10	2	6	6	4	5	7	5
A13	18	16	15	19	18	18	11	18	16	17	16	18
A14	28	28	28	28	28	24	25	28	28	28	28	28
A15	19	19	19	14	14	20	21	19	19	19	18	17
A16	15	17	17	20	19	4	23	14	14	14	21	14
A17	7	7	14	3	20	7	3	5	9	6	10	10
A18	14	14	16	18	11	12	12	15	15	16	15	15
A19	12	11	10	10	3	16	8	11	12	13	11	12
A20	9	9	7	8	6	11	19	9	8	9	8	7
A21	17	18	18	7	24	17	20	16	20	15	17	16
A22	24	24	23	22	25	21	27	24	24	24	24	24
A23	6	5	3	16	2	10	10	7	6	7	5	6
A24	26	26	25	26	26	27	24	26	25	26	26	26
A25	21	22	21	11	23	22	18	22	23	21	20	21
A26	2	3	1	2	5	1	7	3	1	2	2	1
A27	8	8	4	13	7	13	15	13	7	8	6	9
A28	25	25	24	21	21	28	26	25	26	25	23	25

6. Conclusions, limitations, and further research directions

The global economy heavily relies on supply chains for the production and distribution of goods, underscoring their critical importance. However, environmental concerns have increasingly shaped supply chain structures and performance. The implementation of eco-regenerative supply chains is essential for sustainable development and the preservation of resources. Organizations are responding to evolving regulations, consumer preferences, and societal trends by integrating sustainable practices into their supply chains. Traditional supply chains typically prioritize profit, often resulting in environmental harm through resource depletion and pollution. In contrast, eco-regenerative supply chains aim to minimize negative impacts by embracing eco-friendly measures such as renewable energy and waste reduction. Despite the necessity for such transformative measures, the implementation of environmentally sustainable supply chains encounters various challenges.

This study determines and prioritizes 28 barriers to eco-regenerative supply chains utilizing the modified FMEA method. FMEA is a common method of risk analysis due to its wide deployment and consistent analysis. While FMEA is a widely used risk analysis method, it has limitations that researchers aim to address. In this study, an enhanced approach combining FMEA with ZE-SWARA and ZE-MABAC methods is proposed to overcome these limitations. Each method was utilized to cover several shortcomings of the traditional FMEA method so that after determining the probable flaw scenarios based on FMEA, ZE-SWARA is used to count the weight of factors and ZE-MABAC is utilized to prioritize barriers. In the extended methods, because they integrate with the FMEA model, the steps of these methods are implemented in the ZE number context until the last step (calculating the value of each alternative). This is the full ZE-based SWARA-MABAC approach. Both in the weighting phase and the prioritization phase, an integrated ZE context decision framework is provided. The different views of decision-makers and expert team members on the implementation of the FMEA model are unclear. In fact, the proposed approach incorporates fuzzy sets and considers the reliability levels of two distinct groups of decision-makers and experts, offering a robust evaluation framework that accounts for uncertainty. This method enables decision-makers to identify and prioritize critical barriers based on eco-regenerative supply chains acceptance criteria. Comparing the results of the new approach with traditional FMEA methods demonstrates its effectiveness in providing a comprehensive and realistic ranking of barriers.

This study has determined that “High development and implementation costs” are the top priority barrier, scoring 31752. Following closely are “Lack of awareness and knowledge about environmentally friendly technologies in society and organizations” and “Lack of government guarantees and facilities for implementing processes”, ranking second and third with scores of 24192 and 21952, respectively. The proposed method was validated through an analysis test, which confirmed the reliability, accuracy, and robustness of the approach’s outputs. Based on these findings, improvement actions should concentrate on addressing these critical barriers to create favorable conditions for the implementation of eco-regenerative supply chains.

Effective decision-making is crucial in real-world scenarios, highlighting the importance of innovative approaches like the one presented in this study. Nevertheless, it should be acknowledged that processing imprecise information requires intricate mathematical models and formulas. In this regard, artificial intelligence approaches, especially machine learning tools, can help reduce the impact of imprecise information and predictions in order to make the information more transparent. Additionally, this study has limitations regarding the number of experts contributing to the evaluation of strategies. Future research should strive to increase the number of participating experts to enhance the accuracy of strategy evaluations. Furthermore, expanding the scale of ZE linguistic variables and numbers empowers experts to express their opinions with greater freedom and breadth. This finding offers valuable insights for future research: The utilization of more experienced experts can lead to enhanced accuracy and reliability of the results. Additionally, it is advisable to incorporate both the main criteria and sub-criteria for a more precise and comprehensive evaluation of the strategies. Furthermore, given the uncertainty prevalent in real-world problems, it would be beneficial to expand the proposed approach to other uncertain environments, such as grey systems [67], stochastic optimal control [68], and robust optimization [69].

Author contributions

Z. R. Salteh: Conceptualization, Validation, Formal analysis, Resources, Writing—original draft preparation; S. Fazayeli: Validation, Investigation, Data curation, Writing—review and Editing; S. J. Ghoushchi: Conceptualization, Methodology, Supervision, Project administration. All authors have read and approved the final version of the manuscript for publication.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The author declares no conflict of interest.

References

1. Ghoushchi SJ (2018) Qualitative and quantitative analysis of Green Supply Chain Management (GSCM) literature from 2000 to 2015. *Int J Supply Chain Manag* 7: 77–86.
2. Galvin R, Healy N (2020) The Green New Deal in the United States: What it is and how to pay for it. *Energy Res Soc Sci* 67: 101529. https://doi.org/10.1016/j.erss.2020.101529
3. Howard M, Hopkinson P, Miemczyk J (2019) The regenerative supply chain: A framework for developing circular economy indicators. *Int J Prod Res* 57: 7300–7318. https://doi.org/10.1080/00207543.2018.1524166
4. Choudhury NA, Ramkumar M, Schoenherr T, et al. (2023) The role of operations and supply chain management during epidemics and pandemics: Potential and future research opportunities. *Transport Res E-Log* 175: 103139. https://doi.org/10.1016/j.tre.2023.103139
5. Govindan K, Kaliyan M, Kannan D, et al. (2014) Barriers analysis for green supply chain management implementation in Indian industries using analytic hierarchy process. *Int J Prod Econ* 147: 555–568. https://doi.org/10.1016/j.ijpe.2013.08.018
6. Alhamali RM (2019) Critical success factors for green supply chain management practices: An empirical study on data collected from food processing companies in Saudi Arabia. *Afr J Bus Manag* 13: 160–167. https://doi.org/10.5897/AJBM2018.8709
7. Ghoushchi SJ, Asghari M, Mardani A, et al. (2023) Designing an efficient humanitarian supply chain network during an emergency: A scenario-based multi-objective model. *Socio-Econ Plan Sci* 90: 101716. https://doi.org/10.1016/j.seps.2023.101716
8. Davis KF, Downs S, Gephart JA (2021) Towards food supply chain resilience to environmental shocks. *Nat Food* 2: 54–65. https://doi.org/10.1038/s43016-020-00196-3
9. Baloch N, Rashid A (2022) Supply chain networks, complexity, and optimization in developing economies: A systematic literature review and meta-analysis. *South Asian J Oper Log* 1: 1–13. https://doi.org/10.57044/SAJOL.2022.1.1.2202
10. Azam W, Khan I, Ali SA (2023) Alternative energy and natural resources in determining environmental sustainability: A look at the role of government final consumption expenditures in France. *Environ Sci Pollut R* 30: 1949–1965. https://doi.org/10.1007/s11356-022-22334-z
11. Feng Y, Lai KH, Zhu Q (2022) Green supply chain innovation: Emergence, adoption, and challenges. *Int J Prod Econ* 248: 108497. https://doi.org/10.1016/j.ijpe.2022.108497
12. Lis A, Sudolska A, Tomanek M (2020) Mapping research on sustainable supply-chain management. *Sustainability* 12: 3987. https://doi.org/10.3390/su12103987
13. Ghadge A, Jena SK, Kamble S, et al. (2021) Impact of financial risk on supply chains: A manufacturer-supplier relational perspective. *Int J Prod Res* 59: 7090–7105. https://doi.org/10.1080/00207543.2020.1834638

14. Ngo VM, Quang HT, Hoang TG, et al. (2024) Sustainability-related supply chain risks and supply chain performances: The moderating effects of dynamic supply chain management practices. *Bus Strateg Environ* 33: 839–857. https://doi.org/10.1002/bse.3512
15. Eftekharzadeh S, Ghoushchi S, Momayezi F (2024) Enhancing safety and risk management through an integrated spherical fuzzy approach for managing laboratory errors. *Decision Sci Lett* 13: 545–564. https://doi.org/10.5267/j.dsl.2024.5.006
16. Soleimani H, Mohammadi M, Fadaki M, et al. (2021) Carbon-efficient closed-loop supply chain network: An integrated modeling approach under uncertainty. *Environ Sci Pollut R* 1–16. https://doi.org/10.1007/s11356-021-15100-0
17. Azarkamand S, niloufar S (2014) Investigating green supply chain management in Isfahan iron smelting industry and its impact on the development of green performance. *Appl Stud Manag Develop Sci* 4: 15–28. https://doi.org/10.1016/j.spc.2024.06.006
18. Alinejad A, Javad K (2014) Presenting a combined method of ANP and VIKOR in the green supply chain under the gray environment in order to prioritize customers (Case of Study: Fars Oil Products Distribution Company). *Bus Manag* 10. https://doi.org/10.1007/s11356-020-09092-6
19. Soon A, Heidari A, Khalilzadeh M, et al. (2022) Multi-objective sustainable closed-loop supply chain network design considering multiple products with different quality levels. *Systems* 10: 94. https://doi.org/10.3390/systems10040094
20. Hafezalkotob A (2015) Competition of two green and regular supply chains under environmental protection and revenue seeking policies of government. *Comput Ind Eng* 82: 103–114. https://doi.org/10.1016/j.cie.2015.01.016
21. Sheng X, Chen L, Yuan X, et al. (2023) Green supply chain management for a more sustainable manufacturing industry in China: A critical review. *Environ Dev Sustain* 25: 1151–1183. https://doi.org/10.1007/s10668-022-02109-9
22. Oudani M, Sebbar A, Zkik K, et al. (2023) Green Blockchain based IoT for secured supply chain of hazardous materials. *Comput Ind Eng* 175: 108814. https://doi.org/10.1016/j.cie.2022.108814
23. Esfahbodi A, Zhang Y, Watson G (2016) Sustainable supply chain management in emerging economies: Trade-offs between environmental and cost performance. *Int J Prod Econ* 181: 350–366. https://doi.org/10.1016/j.ijpe.2016.02.013
24. Alghababsheh M, Butt AS, Moktadir MA (2022) Business strategy, green supply chain management practices, and financial performance: A nuanced empirical examination. *J Clean Prod* 380: 134865. https://doi.org/10.1016/j.jclepro.2022.134865
25. Falcó JM, García ES, Tudela LAM, et al. (2023) The role of green agriculture and green supply chain management in the green intellectual capital-sustainable performance relationship: A structural equation modeling analysis applied to the Spanish wine industry. *Agriculture* 13: 425. https://doi.org/10.3390/agriculture13020425
26. Ecer F, Ögel İY, Krishankumar R, et al. (2023) The q-rung fuzzy LOPCOW-VIKOR model to assess the role of unmanned aerial vehicles for precision agriculture realization in the Agri-Food 4.0 era. *Artif Intell Rev* 56: 13373–13406. https://doi.org/10.1007/s10462-023-10476-6
27. Karimi A, Ghoushchi SJ, Bonab MM (2020) Presenting a new model for performance measurement of the sustainable supply chain of Shoa Panjereh Company in different provinces of Iran (case study). *Int J Sys Assur Eng* 11: 140–154. https://doi.org/10.1007/s13198-019-00932-4
28. Chatterjee K, Pamucar D, Zavadskas EK (2018) Evaluating the performance of suppliers based on using the R'AMATEL-MAIRCA method for green supply chain implementation in electronics industry. *J Clean Prod* 184: 101–129. https://doi.org/10.1016/j.jclepro.2018.02.186

29. Mondal A, Giri BK, Roy SK, et al. (2024) Sustainable-resilient-responsive supply chain with demand prediction: An interval type-2 robust programming approach. *Eng Appl Artif Intel* 133: 108133. https://doi.org/10.1016/j.engappai.2024.108133
30. Riese J, Fasel H, Pannok M, Lier S. (2024) Decentralized production concepts for bio-based polymers-implications for supply chains, costs, and the carbon footprint. *Sustain Prod Consump* 46: 460–475. https://doi.org/10.1016/j.spc.2024.03.001
31. Ferreira IA, Oliveira J, Antonissen J, et al. (2023) Assessing the impact of fusion-based additive manufacturing technologies on green supply chain management performance. *J Manuf Technol Mana* 34: 187–211. https://doi.org/10.1108/JMTM-06-2022-0235
32. Hiloidhari M, Sharno MA, Baruah D, et al. (2023) Green and sustainable biomass supply chain for environmental, social and economic benefits. *Biomass Bioenerg* 175: 106893. https://doi.org/10.1016/j.biombioe.2023.106893
33. Zhang Z, Yu L (2023) Dynamic decision-making and coordination of low-carbon closed-loop supply chain considering different power structures and government double subsidy. *Clean Technol Envir* 25: 143–171. https://doi.org/10.1007/s10098-022-02394-y
34. de Souza V, Ruwaard JB, Borsato M (2019) Towards regenerative supply networks: A design framework proposal. *J Clean Prod* 221: 145–156. https://doi.org/10.1016/j.jclepro.2019.02.178
35. Khalilpourazari S, Soltanzadeh S, Weber GW, et al. (2020) Designing an efficient blood supply chain network in crisis: Neural learning, optimization and case study. *Ann Oper Res* 289: 123–152. https://doi.org/10.1007/s10479-019-03437-2
36. Fragkos P (2022) Analysing the systemic implications of energy efficiency and circular economy strategies in the decarbonisation context. *AIMS Energy* 10. https://doi.org/10.3934/energy.2022011
37. Tirkolaee EB, Torkayesh AE (2022) A cluster-based stratified hybrid decision support model under uncertainty: Sustainable healthcare landfill location selection. *Appl Intell* 52: 13614–13633. https://doi.org/10.1007/s10489-022-03335-4
38. Tirkolaee EB, Sadeghi S, Mooseloo FM, et al. (2021) Application of machine learning in supply chain management: A comprehensive overview of the main areas. *Math Probl Eng* 2021: 1–14. https://doi.org/10.1155/2021/1476043
39. Bai C, Rezaei J, Sarkis J (2017) Multicriteria green supplier segmentation. *IEEE T Eng Manage* 64: 515–528. https://doi.org/ 10.1109/TEM.2017.2723639
40. Muthuswamy M, Ali AM (2023) Sustainable supply chain management in the age of machine intelligence: Addressing challenges, capitalizing on opportunities, and shaping the future landscape. *Sustain Machine Intell J* 3: 1–14. https://doi.org/10.61185/SMIJ.2023.33103
41. Kumar V, Pallathadka H, Sharma SK, et al. (2022) Role of machine learning in green supply chain management and operations management. *Mater Today Proc* 51: 2485–2489. https://doi.org/10.1016/j.matpr.2021.11.625
42. Wu T, Zuo M (2023) Green supply chain transformation and emission reduction based on machine learning. *Sci Prog* 106. https://doi.org/10.1177/00368504231165679
43. Priore P, Ponte B, Rosillo R (2018) Applying machine learning to the dynamic selection of replenishment policies in fast-changing supply chain environments. *Int J Prod Res* 57. https://doi.org/10.1080/00207543.2018.1552369
44. Ali SS, Kaur R, Ersöz F, et al. (2020) Measuring carbon performance for sustainable green supply chain practices: A developing country scenario. *Cent Eur J Oper Res* 28: 1389–1416. https://doi.org/10.1007/s10100-020-00673-x

45. Barman H, Pervin M, Roy SK, et al. (2023) Analysis of a dual-channel green supply chain game-theoretical model under carbon policy. *Int J Syst Sci-Oper* 10: 2242770. https://doi.org/10.1080/23302674.2023.2242770
46. Lotfi R, Kargar B, Hoseini SH, et al. (2021) Resilience and sustainable supply chain network design by considering renewable energy. *Int J Energ Res* 45: 17749–17766. https://doi.org/10.1002/er.6943
47. Goli A, Tirkolaee EB, Golmohammadi AM, et al. (2023) A robust optimization model to design an IoT-based sustainable supply chain network with flexibility. *Cent Eur J Oper Res* 1–22. https://doi.org/10.1007/s10100-023-00870-4
48. Aytekin A, Okoth BO, Korucuk S, et al. (2022) A neutrosophic approach to evaluate the factors affecting performance and theory of sustainable supply chain management: Application to textile industry. *Manage Decis* 61: 506–529. https://doi.org/10.1108/MD-05-2022-0588
49. Thakur AS (2022) Contextualizing urban sustainability: Limitations, tensions in Indian sustainable-smart urbanism perceived through intranational, international comparisons, and district city Ambala study, *Sustainable Urbanism in Developing Countries*, CRC. Press, 19–39. https://doi.org/10.1201/9781003131922
50. Dhull S, Narwal M (2016) Drivers and barriers in green supply chain management adaptation: A state-of-art review. *Uncertain Supply Chain Manag* 4: 61–76. https://doi.org/10.5267/j.uscm.2015.7.003
51. Bag S, Viktorovich DA, Sahu AK, et al. (2020) Barriers to adoption of blockchain technology in green supply chain management. *J Glob Oper Strateg* 14: 104–133. https://doi.org/10.1108/JGOSS-06-2020-0027
52. Rahman T, Ali SM, Moktadir MA, et al. (2020) Evaluating barriers to implementing green supply chain management: An example from an emerging economy. *Prod Plan Control* 31: 673–698. https://doi.org/10.1080/09537287.2019.1674939
53. Alfina KN, Ratnayake RC, Wibisono D, et al. (2022) *Analyzing barriers towards implementing circular economy in healthcare supply chains*, In: 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE 827–831. https://doi.org/10.1109/IEEM55944.2022.9989999
54. Khiewnavawongsa S, Schmidt EK (2013) *Barriers to green supply chain implementation in the electronics industry*, In: 2013 IEEE international conference on industrial engineering and engineering management, IEEE 226–230. https://doi.org/10.1109/IEEM.2013.6962408
55. Heeres TJ, Tran TM, Noort BA (2023) Drivers and barriers to implementing the internet of things in the health care supply chain: Mixed methods multicase study. *J Med Internet Res* 25: e48730. https://doi.org/10.2196/48730
56. Li J, Sarkis J (2022) Product eco-design practice in green supply chain management: A china-global examination of research. *Nankai Bu Rev Int* 13: 124–153. https://doi.org/10.1108/NBRI-02-2021-0006
57. Okanlawon TT, Oyewobi LO, Jimoh RA (2023) Evaluation of the drivers to the implementation of blockchain technology in the construction supply chain management in Nigeria. *J Financ Manag Prop* 28: 459–476. https://doi.org/10.1108/JFMPC-11-2022-0058
58. Shrivastav M (2021) Barriers related to AI implementation in supply chain management. *J Glob Inf Manag* 30: 1–19. https://doi.org/10.4018/JGIM.296725
59. Mathiyazhagan K, Datta U, Bhadauria R, et al. (2018) Identification and prioritization of motivational factors for the green supply chain management adoption: Case from Indian construction industries. *Opsearch* 55: 202–219. https://doi.org/10.1007/s12597-017-0316-7

60. Bey N, Hauschild MZ, McAloone TC (2013) Drivers and barriers for implementation of environmental strategies in manufacturing companies. *Cirp Ann* 62: 43–46. https://doi.org/10.1016/j.cirp.2013.03.001
61. Zadeh LA (1965) Fuzzy sets. *Inf Control* 8: 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X
62. Wang F (2021) Preference degree of triangular fuzzy numbers and its application to multi-attribute group decision making. *Expert Syst App* 178: 114982. https://doi.org/10.1016/j.eswa.2021.114982
63. Tešić D, Božanić D, Khalilzadeh M (2024) Enhancing multi-criteria decision-making with fuzzy logic: An advanced defining interrelationships between ranked II method incorporating triangular fuzzy numbers. *J Intel Manag Decis* 3: 56–67. https://doi.org/10.56578/jimd030105
64. Zadeh LA (2011) A note on Z-numbers. *Inf Sci* 181: 2923–2932. https://doi.org/10.1016/j.ins.2011.02.022
65. Tian Y, Mi X, Ji Y, et al. (2021) ZE-numbers: A new extended Z-numbers and its application on multiple attribute group decision making. *Eng Appl Artif Intel* 101: 104225. https://doi.org/10.1016/j.engappai.2021.104225
66. Stanujkic D, Karabasevic D, Zavadskas EK (2015) A framework for the selection of a packaging design based on the SWARA method. *Eng Econ* 26: 181–187. https://doi.org/10.5755/j01.ee.26.2.8820
67. Roy SK, Maity G, Weber GW (2017) Multi-objective two-stage grey transportation problem using utility function with goals. *Cent Eur J Oper Res* 25: 417–439. https://doi.org/10.1007/s10100-016-0464-5
68. Savku E, Weber GW (2018) A stochastic maximum principle for a Markov regime-switching jump-diffusion model with delay and an application to finance. *J Optimiz Theory App* 179: 696–721. https://doi.org/10.1007/s10957-017-1159-3
69. Özmen A, Kropat E, Weber GW (2017) Robust optimization in spline regression models for multi-model regulatory networks under polyhedral uncertainty. *Optimization* 66: 2135–2155. https://doi.org/10.1080/02331934.2016.1209672