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ORIGINAL RESEARCH

A hybrid fermatean fuzzy framework for evaluating climate-responsive supply network strategies

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Abstract
Despite the growing importance of climate change adaptation, current studies offer limited methodologies for selecting optimal supply network strategies under uncertain and dynamic environmental conditions. This study aims to fill this gap by identifying and prioritizing the most suitable supply network strategies considering sustainability and climate change impacts. A novel hybrid multi-criteria decision-making (MCDM) approach is developed, integrating Fermatean Fuzzy Analytical Hierarchy Process (FF-AHP) and Fermatean Fuzzy Weighted Integrated Sum Product (FF-WISP) methods to address uncertainty and complexity in the decision-making process. First, a comprehensive hierarchical evaluation framework, consisting of three levels of criteria, including environmental, resilience, and socioeconomic dimensions, was developed through literature review and expert input. FF-AHP was applied to calculate the relative importance of these criteria, while FF-WISP ranked four strategic alternatives. The results highlight Hybrid (Global + Local) with Flexible Logistics as the most effective strategy, followed by Regional Sourcing with High-Resilience Investment. Sensitivity analysis with randomized expert weights confirmed the robustness of the proposed model. This study contributes a flexible and practical decision-support tool for policymakers and supply chain managers facing climate uncertainty. Future research may extend this model by integrating smart logistics technologies and renewable energy-based criteria for broader sustainability applications.

Keywords Supply networks · Multi-criteria optimization · Fermatean fuzzy sets · Sustainability · Climate change

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1 Introduction

Climate change is a rapidly increasing major crisis in the world. Extreme weather conditions, such as heavy rainfall, heat waves, and drought, cause major damage to infrastructure and power lines, as well as adverse health effects (Bag et al., 2023). Additionally, such extreme weather events and climate change increasingly destabilize global transportation systems, creating significant uncertainty and operational troubles (Guitouni et al., 2025). Also, mitigating climate change is one of the greatest problems facing societies, which is closely connected to the topic of the future energy system (Potrč et al., 2021).

Since these problems caused by climate change can easily impact the supply chain network, the production and transactions of industrial products are also affected (Li et al., 2025). Unpredictable extreme events and disruptions due to climate change are considered an essential part of the supply chain network (Zavala et al., 2019). For instance, the extreme heat wave in China caused reduced food production and even food shortages and price increases in both local and global food supply chains (Ali et al., 2023).

As climate change affects both social and commercial activities, many countries face many challenges, such as uneven development across different regions, resource scarcity, and difficulty in adaptation (Li et al., 2025). Adopting climate change conditions of supply networks has many advantages, such as less environmental pollution, combating industrial waste, adaptation to extreme conditions, and sustainability. Thus, designing a supply chain network under climate change conditions may support sustainability and environmental protection. Sensitivity of the industrial sector to climate change may help them recognize variations in exposure to climate change across regions and respond to climate change in their regions (Li et al., 2025). Given the uncertainty of future climate conditions, sound planning and decision-making processes are critical (Guitouni et al., 2025). This study presents a novel framework for supply networks in the face of climate change.

In this context, the selection of appropriate supply network strategies becomes a critical factor in building climate-resilient and sustainable operations. As supply chains are increasingly exposed to climate-related disruptions, decision-makers must not only anticipate risks but also proactively choose strategies that can withstand or adapt to varying environmental conditions. Strategic choices, such as sourcing models, inventory policies, and logistics flexibility, can significantly influence a supply network's ability to maintain functionality during extreme weather events. Therefore, identifying and implementing the most suitable strategy under climate uncertainty is essential for minimizing disruptions, preserving supply continuity, and supporting long-term sustainability goals. A well-structured strategy enables firms to optimize operational efficiency while reducing environmental impacts, enhancing adaptability, and ensuring economic resilience. This study addresses this pressing need by proposing a systematic decision-making model to evaluate and prioritize supply network strategies in response to climate change challenges.

This study aims to identify and prioritize supply network strategies in response to the growing challenges posed by climate change. The primary objective is to determine the most effective and appropriate strategy among several alternatives, based on a comprehensive set of evaluation criteria. These criteria were established through an extensive literature review and validated by expert input, ensuring a robust and context-specific assessment framework that incorporates both sustainability and climate-related considerations. To achieve this goal, the study introduces a novel hybrid multi-criteria decision-making (MCDM) approach to address the uncertainty and complexity inherent in strategic supply network decision-making under climate uncertainty.

This study aims to address the current gap in the literature by examining the prioritized supply networks in the face of climate change. To achieve this, the study seeks to answer the following research questions:

RQ1-How can sustainability ideologies be successfully integrated into the supply network in the face of climate change?

RQ2-How can the decision-making process for optimization of supply networks be improved with a fuzzy-based framework?

The main contributions of this study can be summarized as:

- This study determines the most suitable supply network under climate change conditions by using a novel hybrid MCDM approach.
- Several criteria are identified via an extensive literature review and expert opinions, such as environmental impact, climate vulnerability, climate adaptation investment, resource efficiency, etc.
- Different from the literature, this study proposes the FF-AHP method to calculate the criteria weights and integrates this method with the FF-WISP to rank the alternatives.
- Integrating FF-AHP and FF-WISP within a fuzzy framework allows for a more nuanced valuation by successfully addressing uncertainties and complexities in the decision-making procedure.

The remainder of this paper is organized as follows: Sect. 2 summarizes the related works. Section 3 proves the proposed methodology. Section 4 suggests the application, which includes the weighting of criteria and the ranking of the alternatives, and the discussion is given in Sect. 5. The last section gives concluding remarks and directions for future work.

2 Literature review

This section presents a detailed literature review to provide a theoretical basis and information on supply network optimization studies in the context of climate change. This comprehensive review aims to provide a solid background and guide for future work. For this purpose, the SCOPUS database was used to access the above-mentioned studies. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was used to ensure methodical progress during the literature review. This approach, which has become popular in recent years for conducting comprehensive literature reviews, was proposed by Moher et al. (2010). The first stage determines eligibility criteria, the second analyzes and evaluates sources, and the third selects suitable parts of the literature. The final stages contain data collection and selection of data elements, respectively (E. Ayyildiz & Erdogan, 2023; Santi & Putra, 2018).

In this context, the following keywords were used to search for this study and 47 documents were found in the SCOPUS platform: *"MCDM" OR "multi-criteria decision making" OR "multicriteria decision making" OR "multi-criteria decision analysis" OR "multicriteria decision analysis" OR "MADM" OR "multiple attribute decision making" OR "multiple attribute decision analysis" OR "AHP" OR "analytic hierarchy process" OR "TOPSIS" OR "VIKOR" OR "PROMETHEE" OR "ELECTRE" OR "MOORA" OR "COPRAS" OR "BEST WORST" OR "BWM" OR "CODAS" OR "EDAS" OR "WASPAS") AND TITLE-ABS-KEY ("supply chain" OR "logistics network" OR "distribution network" OR "supply network") AND TITLE-ABS-KEY ("resilience" OR "resilient" OR "robust" OR "robustness" OR "uncertainty") AND TITLE-ABS-KEY ("climate change" OR "extreme weather" OR "global warming"*. Among these articles, those in the field of supply network optimization were selected. The related

studies are summarized in Table 1. Moreover, this technique stresses the novelty of the framework suggested.

The articles most similar to this study, which can form the basis, have been examined in detail. Many studies have evaluated supply chains in terms of climate change vulnerability (Li et al., 2025), (Guitouni et al., 2025), (Ali et al., 2023), (Bag et al., 2023). Firstly, when the related literature is scanned in detail, it is seen that there are limited studies, especially on supply network selection. The first thing that draws attention in Table 1 is that supply network concept studies are generally related to network design. In addition, it is seen that MCDM methods are frequently used in the studies conducted, as in decision-making problems such as location selection, strategy selection, etc. Also, it has been determined that fuzzy logic, which is one of the best ways to reflect uncertainty in decision-making problems, has not yet found sufficient place in current studies, and no calculations have been made with extended fuzzy numbers. In addition, fuzzy logic and detailed calculations made with extended fuzzy numbers, which are the most effective methods of reflecting uncertainty in decision-making problems, are not adequately addressed in existing studies. In some fuzzy-based studies, traditional or triangular sets are used. (Nguyen et al., 2024), (Sabouhi et al., 2021), (Robles et al., 2020). However, Li et al. and Mobarezkhoo et al. used traditional MCDM approaches such as TOPSIS and BWM and considered classical criteria such as economic, social, and environmental (Li et al., 2025), (Mobarezkhoo et al., 2022). Therefore, the focus of the studies in the existing literature, their solution approaches, and the differences in the criteria they addressed from this study are shown in Table 1.

A decision-making approach should be developed in light of many criteria under important issues, such as climate change, for the selection of a sustainable supply network. This study determines the most suitable supply network under climate change conditions to fill these gaps in the literature. For this purpose, it presents a hybrid novel MCDM approach under a fuzzy environment that allows the simultaneous evaluation of many conflicting criteria. With extended Fermatean Fuzzy Sets (FFSs), a large number of expert opinions are used to obtain findings from a linguistic perspective. This approach is particularly effective in complex decision-making problems involving conflicting criteria under uncertainty, where traditional fuzzy approaches such as Intuitive and Pythagorean fuzzy sets may be inadequate (details are provided in Sect. 3). When the studies in the literature and Table 1 are examined in general, it is seen that the selection of the supply network is not addressed with such a comprehensive set of criteria, expert opinions, and the novel hybrid MCDM approach. Thus, this study will be a guide for future research.

3 Proposed methodology

This study proposes an innovative hybrid decision-making methodology to identify the most effective strategy for managing risks in supply networks under climate change. The methodology, termed FF-WISP, introduces a novel integration of Fermatean fuzzy logic with the traditional WISP method. Furthermore, this approach presents the first known combination of the AHP and WISP within a Fermatean fuzzy environment, thus offering a robust framework for addressing complex MCDM problems characterized by uncertainty.

The process begins with the application of the FF-AHP to determine the relative importance of evaluation criteria across hierarchical levels. Pairwise comparison matrices (PCMs) are used to capture expert judgments, which are then aggregated and tested for consistency. The derived criteria weights reflect the nested structure of main criteria, sub-criteria, and

Table 1 Summary of related studies on climate-aware supply network optimization/evaluation

Ref	Year	Problem	Method	Fuzzy set	Proposed criteria	Application area
(Li et al., 2025)	2025	Evaluating climate vulnerability for industrial supply chains	Technique for Order Preference by Similarity to an Ideal Solution Based on Entropy (TOPSIS-Entropy), Multi-Region Input–Output Analysis (MRIO),	-	Exposure, sensitivity, adaptation—9 sub-criteria	China
(Guitouni et al., 2025)	2025	Evaluating the resilience of supply chains under climate change	Monte Carlo simulation	–	Low emissions, moderate emissions, high emissions	Canada
(Ali et al., 2023)	2023	Supply chain resilience to climate change	Hypothesis testing, Mediation analysis, Moderation analysis	–	Firm size, managerial positions, experience, agri-food industry sub-sectors, etc	Australian agri-food industry
(Kagawa et al., 2015)	2015	Clustering CO_2 emissions of supply chain networks under climate change	Multiregional input–output analysis, Cluster analysis	–	Carbon emission	China
(Potrč et al., 2021)	2021	Optimization of renewable energy supply networks	Mixed-integer programming model	–	Economic, environmental, and social	European Union
(Bag et al., 2023)	2023	Testing Climate change adaptation and disaster risk reduction goals in the supply chain network	Hypothesis testing, structural equation modeling	–	Multinational enterprises' customer pressures, non-multinational enterprises' customer pressures, Compliance of local suppliers to climate change adaptation and the disaster risk reduction goals etc	Bangladesh

Table 1 (continued)

Ref	Year	Problem	Method	Fuzzy set	Proposed criteria	Application area
(Mobarezkhoo et al., 2022)	2022	Evaluating the supply network life cycle	Data Envelopment Analysis Approach (DEA), Combinative Distance-Based Assessment (CODAS), Best Worst Method (BWM)	–	Economic, social and environmental	Iran
(Gilani & Sahebi, 2021)	2021	Optimizing the sugarcane-to-biofuel supply network design	Mixed-integer linear programming model	–	Cost, environmental impacts	Iran
(Nguyen et al., 2024)	2024	Evaluating and prioritizing circular supply chain alternatives	Holistic Multi-Indicator Decision Support System, Entropy, PROMETHEE II, Fuzzy Analytic Hierarchy Process (AHP)	Traditional	Circularity, environment-energy, economy, society—49 sub-criteria	Italy
(Sabouhi et al., 2021)	2025	Optimization of photovoltaic supply chain network design	Fuzzy BWM, TOPSIS, optimization model	Triangular	Height of foundation, reservoir volume, average daily short-wave solar energy, average annual chance of precipitation, average annual cloud cover, easy access	Iran
(Mirkouei et al., 2017)	2017	Mixed biomass-based energy supply chain design under upstream challenges	Stochastic model, genetic algorithm	–	Cost, environmental impacts	Pacific Northwest
(Robles et al., 2020)	2020	Optimization of the hydrogen supply chain network design	Multi-objective genetic algorithms, modified TOPSIS	Traditional	Cost, safety, and environmental	France

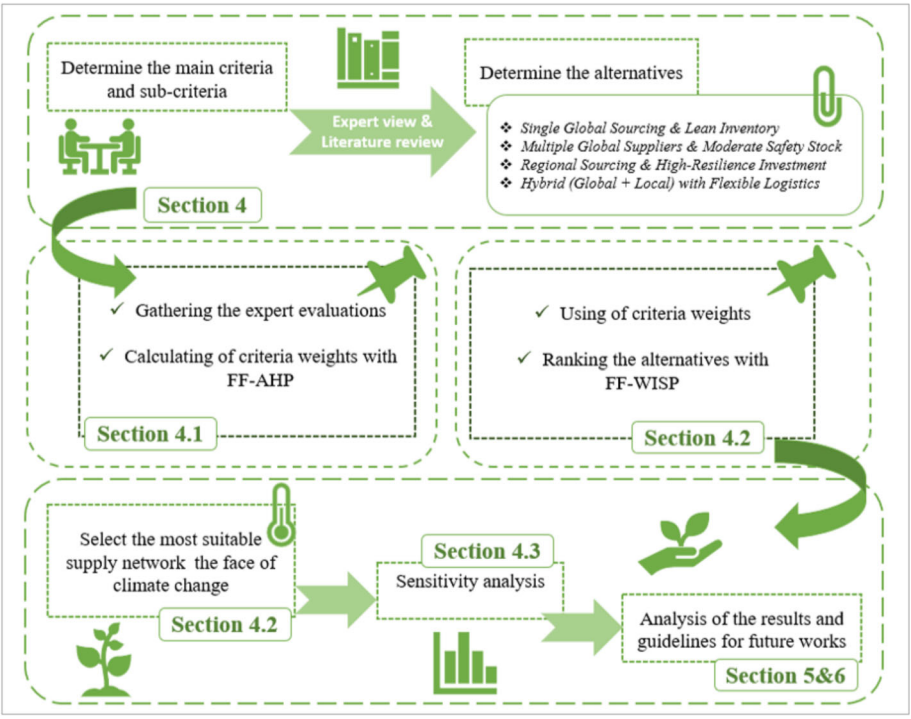


Fig. 1 Workflow of the proposed FF-AHP–FF-WISP decision framework for climate-responsive supply network evaluation

related dimensions relevant to sustainable and climate-resilient supply networks. Following the weighting stage, the FF-WISP is employed to assess and prioritize the strategic alternatives. Unlike conventional WISP approaches that rely on basic normalization and utility scoring, the FF-WISP method leverages the expressive capabilities of FFSs to account for vagueness, hesitation, and uncertainty in expert evaluations. This enables more realistic and nuanced assessments in complex decision environments. A visual representation of the proposed methodology's workflow is provided in Fig. 1, outlining the sequential integration of FF-AHP and FF-WISP in evaluating alternative supply network strategies.

3.1 Preliminaries

In complex decision-making problems, particularly those involving conflicting criteria under uncertainty, traditional fuzzy approaches such as Intuitionistic and Pythagorean fuzzy sets may fall short. This limitation stems from the structural constraints imposed on the membership and non-membership degrees—specifically, their sum (in Intuitionistic) or squared sum (in Pythagorean) must not exceed 1. These constraints narrow the representation space and may restrict the ability to model expert hesitations or ambiguity effectively.

In contrast, FFSs, introduced by Senapati and Yager (Senapati & Yager, 2019), overcome this restriction by allowing the sum of the cubes of membership (μ) and non-membership (ν) degrees to be at most 1. This expanded flexibility enables a richer expression of uncertainty and greater tolerance for ambiguity in expert evaluations. FFSs have thus emerged

as a promising tool for translating subjective judgments into a mathematically robust form, particularly in MCDM under uncertain or imprecise environments (Garg et al., 2020).

Definition 1 A Fermatean Fuzzy Number (FFN) is formally defined over a reference set X (Senapati & Yager, 2019).

$$\widetilde{F} \cong \left\{x, \mu_{\widetilde{F}}(x), v_{\widetilde{F}}(x); x \in X\right\} \tag{1}$$

where

$$0 \leq \mu_{\widetilde{F}}(x)^3 + v_{\widetilde{F}}(x)^3 \leq 1 \tag{2}$$

$\mu_{\widetilde{F}}(x) : X \mapsto [0, 1]$ and $v_{\widetilde{F}}(x) : X \mapsto [0, 1]$ define the membership and non-membership degrees.

The degree of hesitancy:

$$\pi_{\widetilde{p}}(x) = \sqrt[3]{1 - (\mu_{\widetilde{F}}(x))^3 + (v_{\widetilde{F}}(x)^3)} \tag{3}$$

Let $\widetilde{\alpha} = (\mu_{\widetilde{\alpha}}, v_{\widetilde{\alpha}})$ and $\widetilde{\beta} = (\mu_{\widetilde{\beta}}, v_{\widetilde{\beta}})$ are FFN.

Definition 2 Multiplication by a positive scalar and a positive power:

$$\lambda\widetilde{\alpha} = \left(\sqrt[3]{1 - \left(1 - \mu_{\widetilde{\alpha}}^3\right)^{\lambda}}, v_{\widetilde{\alpha}}^{\lambda}\right) \tag{4}$$

$$\widetilde{\alpha}^{\lambda} = \left(\mu_{\widetilde{\alpha}}^{\lambda}, \sqrt[3]{1 - \left(1 - v_{\widetilde{\alpha}}^3\right)^{\lambda}}\right) \tag{5}$$

Definition 3 Multiplication and summation:

$$\widetilde{\alpha} \otimes \widetilde{\beta} = \left(\mu_{\widetilde{\alpha}}\mu_{\widetilde{\beta}}, \sqrt[3]{v_{\widetilde{\alpha}}^3 + v_{\widetilde{\beta}}^3 - v_{\widetilde{\alpha}}^3 v_{\widetilde{\beta}}^3}\right) \tag{6}$$

$$\widetilde{\alpha} \oplus \widetilde{\beta} = \left(\sqrt[3]{\mu_{\widetilde{\alpha}}^3 + \mu_{\widetilde{\beta}}^3 - \mu_{\widetilde{\alpha}}^3\mu_{\widetilde{\beta}}^3}, v_{\widetilde{\alpha}}v_{\widetilde{\beta}}\right) \tag{7}$$

Definition 4 The score function (Gonzales et al., 2022) and score index (Ayvaz et al., 2024):

$$S^F(\widetilde{\alpha}) = \frac{1}{2}\left[\left((\mu_{\widetilde{\alpha}})^3 - (v_{\widetilde{\alpha}})^3 - \ln\left(1 + (\pi_{\widetilde{\alpha}})^3\right)\right) + 1\right] \tag{8}$$

$$SI(\widetilde{\alpha}) = (\mu_{\widetilde{\alpha}})^3 - (v_{\widetilde{\alpha}})^3 \tag{9}$$

Definition 7 The Fermatean Fuzzy Weighted Operator (FFW) (Erdogan & Ayyildiz, 2022) and the Fermatean Fuzzy Weighted Geometric (FFWG) operator is (Senapati & Yager, 2019):

$$FFW(\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_n) = \left(\sqrt[3]{1 - \prod_{i=1}^{n}\left(1 - \left(\mu_{\mathcal{F}_i}\right)^3\right)^{w_i}}, \prod_{i=1}^{n}\left(v_{\mathcal{F}_i}\right)^{w_i}\right) \tag{10}$$

$$FFWG(\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_n) = \left(\prod_{i=1}^{n}\mu_{\mathcal{F}_i}^{w_i}, \prod_{i=1}^{n}v_{\mathcal{F}_i}^{w_i}\right) \tag{11}$$

where $\mathcal{F}_i = \left(\mu_{F_i}, v_{F_i}\right)$ and $w = (w_1, w_2, \ldots, w_n)^T$ are the set of FFNs and the weight vector, respectively.

3.2 Fermatean fuzzy AHP

FF-AHP builds upon the classical AHP developed by Saaty (Saaty, 1980), a widely recognized method for solving decision problems involving quantitative and qualitative criteria. AHP provides a structured and transparent approach for decision-making by organizing complex problems into hierarchical levels and allowing decision-makers to make pairwise comparisons between criteria. One of its key strengths is its ability to incorporate subjective judgments, making it highly applicable in both individual and group decision contexts (Ertugrul Ayyildiz & Taskin Gumus, 2020). Fuzzy extensions of AHP have been developed to better manage ambiguity and vagueness in expert evaluations. These models integrate fuzzy logic and fuzzy set theory, enabling more flexible representations of linguistic preferences (Ertugrul Ayyildiz, 2022; Yildiz et al., 2020). Among these, FF-AHP stands out by incorporating FFSs, which allow for a broader and more expressive modeling of uncertainty compared to intuitionistic and Pythagorean fuzzy sets. FF-AHP enhances the decision-making process by capturing hesitancy, inconsistency, and ambiguity more effectively (Ayvaz et al., 2024). In this study, the FF-AHP method is applied to determine the relative importance of evaluation criteria in a climate-aware supply chain context. The methodological steps are outlined as follows:

Step 1. Each expert provides judgments using linguistic terms (as defined in Table 2), which are then converted into FFNs.

Step 2. The consistency of each PCM is evaluated based on Saaty's consistency index (CI), utilizing the Score Index (SI) values provided in Table 2.

To determine the consistency ratio (CR) of a decision matrix, the first step is to calculate its CI based on the eigenvalue method proposed by Saaty. The CI is obtained using:.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{12}$$

where λ_{max} represents the largest (principal) eigenvalue of the decision matrix A, and n denotes the matrix size. Next, the consistency ratio is computed as

$$CR = \frac{CI}{RI} \tag{13}$$

Here, the random index (RI) depends on the order of the matrix (n) and is derived from the reference table developed by Saaty. A matrix is considered consistent if the CR value is less than or equal to 0.1, indicating that the pairwise comparisons are logically coherent and reliable.

Table 2 Linguistic scale for FF-AHP pairwise comparisons: Score Index (SI) terms and corresponding Fermatean Fuzzy Numbers (FFNs) used to construct expert PCMs

SI	Term	FFN	SI	Term	FFN
9	CH: Certainly high importance	(0.97, 0.233)	1/9	CL: Certainly less importance	(0.224, 0.05)
7	VH: Very high importance	(0.9, 0.307)	1/7	VL: Very less importance	(0.243, 0.04)
5	H: High importance	(0.794, 0.083)	1/5	L: Less importance	(0.272, 0.05)
3	MH: Medium more importance	(0.67, 0.091)	1/3	MLI: Medium less importance	(0.322, 0.038)
1	E: Equal importance	(0.465, 0.082)			

Step 3. The FFW operator is applied to aggregate the individual PCMs into a group consensus matrix.

Step 4. The FFWG operator is used to compute the local weights of each criterion row-wise in the aggregated matrix.

Step 5. Unnormalized criterion weights (uw_j) are derived using the score function based on the Fermatean fuzzy outputs.

Step 6. The final weights for all criteria are obtained through normalization.

$$w_j = \frac{uw_j}{\sum_{j=1}^{n} uw_j} \tag{14}$$

where n is the number of criteria.

3.3 Fermatean fuzzy WISP

Traditional MCDM methods are generally classified into two main categories: utility-based approaches, which are user-friendly and widely applicable (Hafezalkotob et al., 2019), and outranking methods, which, while more analytical, tend to become computationally burdensome when dealing with a large number of alternatives (Rani et al., 2023). Among these, the WISP method has gained attention for its simplicity, computational efficiency, and ability to evaluate benefit and cost-type criteria simultaneously.

The WISP approach, originally proposed by Stanujkic et al. (2023), merges the strengths of the Weighted Sum Model (WSM) and the Weighted Product Model (WPM). By combining these techniques, WISP simplifies the normalization process and employs four distinct utility measures to calculate the comprehensive utility score of each alternative, thereby facilitating more straightforward and transparent rankings (Stanujkic et al., 2022). Recent studies suggest that WISP achieves more robust and reliable results than many conventional MCDM methods by utilizing multiple utility perspectives (Görçün et al., 2024).

WISP is used in this study instead of classical benchmarks such as TOPSIS, VIKOR, or PROMETHEE because WISP integrates additive (WSM) and multiplicative (WPM) aggregation into a single scheme and evaluates alternatives through multiple utility measures, yielding balanced compensation between benefit and cost criteria and reducing ranking sensitivity to any single normalization or operator. Prior comparative studies show that WISP's rankings are highly correlated with prominent MCDM methods while retaining transparent computations suitable for extensive sensitivity analysis (Stanujkić et al., 2021). Methodological analyses further report the robustness of WISP under different normalization procedures and its alignment with results from other methods, supporting reliability in practice (Zavadskas et al., 2022a, 2022b). In climate-oriented supply network evaluation, this WSM + WPM balance is crucial to avoid the anomalies of purely additive or purely multiplicative models, considering the trade-offs across environmental, resilience, and economic dimensions are non-linear and mixed-type (benefit/cost). Moreover, recent fuzzy extensions of WISP demonstrate its compatibility with uncertainty modeling, reinforcing its suitability for our Fermatean fuzzy framework (Zavadskas et al., 2022a, 2022b).

While several extensions of the WISP method have been proposed using various fuzzy environments and real-world applications (Rani et al., 2024), this study presents the first adaptation of WISP within a Fermatean fuzzy framework. This research introduces the FF-WISP model to address the limitations of earlier fuzzy approaches (e.g., intuitionistic and Pythagorean sets), which impose restrictive conditions on membership values. This enhanced

Table 3 Linguistic terms and FFNs used in FF-WISP to rate alternative performance

Term	FFN	Term	FFN
EG: Extremely Good	(0.99, 0.1)	EB: Extremely Bad	(0.01, 0.99)
VG: Very Good	(0.9, 0.2)	VB: Very Bad	(0.1, 0.9)
G: Good	(0.8, 0.3)	B: Bad	(0.2, 0.8)
MG: Medium Good	(0.65, 0.4)	MB: Medium Bad	(0.35, 0.7)
F: Fair	(0.5, 0.5)		

version of WISP integrates FFSs to provide a more expressive and accurate representation of uncertainty and expert hesitancy in decision-making.

The proposed FF-WISP method strengthens the classical WISP by improving the handling of ambiguous and imprecise information, ensuring more rigorous evaluations and intuitive rankings of strategic alternatives. The procedural steps of the FF-WISP methodology are outlined below.

Step 1. Each alternative is evaluated with respect to the defined criteria using the linguistic terms provided in Table 3 (Aydoğan & Özkir, 2023).

Step 2. Expert judgments are aggregated using the FFW operator to generate collective fuzzy decisions.

Step 3. The aggregated fuzzy values are defuzzied and converted into crisp scores through the use of a score function.

Step 4. The WSM values for each alternative are computed by considering the nature of each criterion:

For benefit-type criteria:

$$ws_i^{max} = \sum_{j \in \Omega_{max}} r_{ij} w_j \tag{15}$$

For cost-type criteria:

$$ws_i^{min} = \sum_{j \in \Omega_{min}} r_{ij} w_j \tag{16}$$

Step 5. The WPM values for each alternative are calculated similarly.

For benefit-type criteria:

$$wp_i^{max} = \prod_{j \in \Omega_{max}} r_{ij} w_j \tag{17}$$

For cost-type criteria:

$$wp_i^{min} = \prod_{j \in \Omega_{min}} r_{ij} w_j \tag{18}$$

Here, w_j represents the weight of criterion j, obtained through the FF-AHP process.

Step 6. Four utility measures are calculated for each alternative.

Simple difference (additive) between WSM and WPM values:

$$u_i^{sd} = ws_i^{max} - ws_i^{min} \tag{19}$$

$$u_i^{pd} = wp_i^{max} - ws_i^{min} \tag{20}$$

Simple ratio (multiplicative) between WSM and WPM values:

$$u_i^{sr} = \frac{ws_i^{max}}{ws_i^{min}} \tag{21}$$

$$u_i^{pr} = \frac{wp_i^{max}}{wp_i^{min}} \tag{22}$$

These measures reflect both the absolute and relative utility of each alternative.

Step 7. Utility values are normalized to ensure comparability on a unified scale.

$$\overline{u}_i^{sd} = \frac{1 + u_i^{sd}}{1 + \underset{i}{max} u_i^{sd}} \tag{23}$$

$$\overline{u}_i^{pd} = \frac{1 + u_i^{pd}}{1 + \underset{i}{max} u_i^{pd}} \tag{24}$$

$$\overline{u}_i^{sr} = \frac{1 + u_i^{sr}}{1 + \underset{i}{max} u_i^{sr}} \tag{25}$$

$$\overline{u}_i^{pr} = \frac{1 + u_i^{pr}}{1 + \underset{i}{max} u_i^{pr}} \tag{26}$$

Note: If the decision problem includes only benefit-type criteria, Eqs. (21) and (22) should be adapted as follows:

$$u_i^{sr} = \sum_{j \in \Omega_{max}} r_{ij} w_j \tag{27}$$

$$u_i^{pr} = \prod_{j \in \Omega_{max}} r_{ij} w_j \tag{28}$$

Step 8. The overall utility score for each alternative is calculated as the average of the four normalized utility measures:

$$u_i = \frac{1}{4}\left(\overline{u}_i^{sd} + \overline{u}_i^{pd} + \overline{u}_i^{sr} + \overline{u}_i^{pr}\right) \tag{29}$$

4 Application

This study aims to identify the most effective and suitable supply network under climate change conditions. For this goal, 3-Level criteria sets were defined. This first level identifies the main criteria, the second level identifies sub-criteria, and the third level identifies sub-criteria based on Level 2. This comprehensive set of criteria, determined through literature review and expert opinions, is defined in Table 4.

With the help of literature and expert views, four alternative supply networks were determined. These alternatives are given in Fig. 2.

After determining the criteria set and alternatives, the weighting process for these criteria and sub-criteria uses the FF-AHP method, which systematically integrates nine expert views through FFNs to account for uncertainties and subjectivity. These experts provided their

Table 4 Three-level criteria hierarchy with concise definitions for climate-responsive supply network evaluation

Level 1 Criteria	Level 2 Criteria	Level 3 Criteria	Definitions
C1. Environmental Sustainability	C11. Environmental Impact	Pollution & Waste Generation	The generation level of pollution and waste from supply chain processes
		Biodiversity & Habitat Preservation	Impact of operations on ecosystems and biodiversity in affected regions
		Hazardous Material Usage	Consumption of hazardous materials within sourcing and production
	C12. Resource Efficiency	Energy Efficiency	Efficiency of energy utilization across production and logistics operations
		Water Usage	Level of water consumption within supply chain operations
		Material Conservation	Use of recycled/reusable materials and circular economy practices
	C13. Climate Mitigation	Renewable Energy Integration	Use of renewable energy sources within supply chain operations
		Waste-to-Energy Practices	The extent of converting operational waste into usable energy, reducing environmental impact
		Low-Emission Logistics	Adoption level of low-emission transportation methods across the supply chain
C2. Climate Resilience	C21. Climate Vulnerability	Exposure to Extreme Weather	Degree of vulnerability to extreme weather events due to geographical sourcing

Table 4 (continued)

Level 1 Criteria	Level 2 Criteria	Level 3 Criteria	Definitions
		Time to Recover from Disruptions	The speed at which normal operations resume following climate disruptions
		Backup Resources	Availability of alternative resources or backup facilities during supply disruptions
	C22. Climate Adaptation Investment	Infrastructure Upgrades	Investment in physical improvements to protect the supply chain from climate risks
		Technology & Monitoring Systems	Investment in climate event monitoring and early-warning technological systems
		Emergency Preparedness & Training	Level of preparedness and training programs for climate-related emergencies
	C23. Technological Flexibility	Digitalization & Automation	The extent of adopting digital tools to manage climate risks and disruptions
		Innovation Capability	The capacity to integrate new climate-resilient technologies quickly
		Flexibility of Infrastructure	Ease of modifying existing facilities/systems in response to climate-related requirements
C3. Socioeconomic Factors	C31. Economic Cost	Logistic Cost	Costs associated with transportation, warehousing, and logistics management
		Operational Cost	Total operating cost, including labor, materials, and daily operations
		Investment Cost	Capital investment required for establishing the supply chain and resilience measures

Table 4 (continued)

Level 1 Criteria	Level 2 Criteria	Level 3 Criteria	Definitions
	C32. Policy Alignment	Carbon Policy Compliance	Alignment with carbon regulations (carbon taxes, emission trading)
		Environmental Standards & Certifications	Compliance with recognized environmental management standards (ISO 14001, etc.)
		Reporting & Transparency	Level of transparency in sustainability reporting practices
	C33. Community Impact	Local Community Welfare	Contribution of supply chain operations to local community development and welfare
		Job Creation & Fair Labor Practices	Creation of employment opportunities and adherence to fair labor practices
		Stakeholder Engagement & Acceptance	Level of engagement and acceptance from community stakeholders

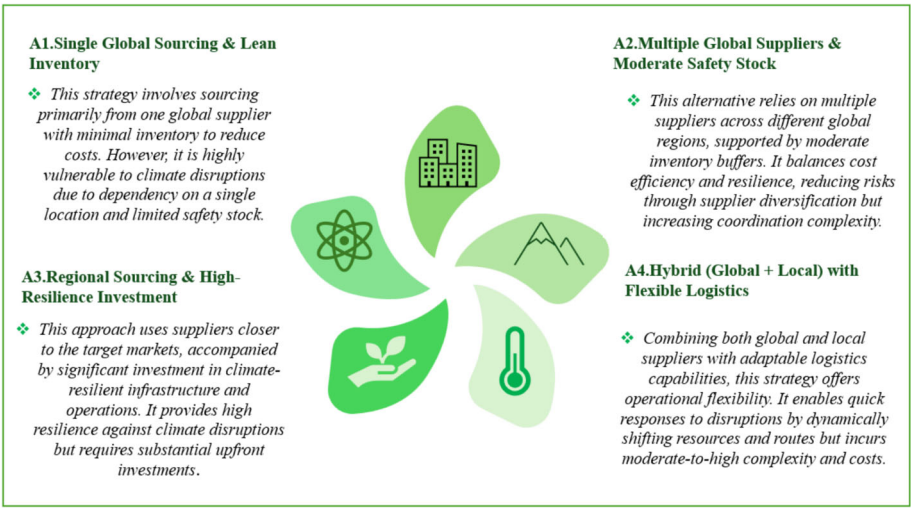


Fig. 2 Evaluated alternative strategies

assessments with linguistic terms, which were then converted into FFNs to capture the degrees of membership, non-membership, and hesitation. Moreover, the FF-WISP method enabled the aggregation of these assessments, followed by exact weightings for each criterion that reflect both the experts' visions and the inherent uncertainties in their decisions. Finally, with the FF-WISP method, alternatives were ranked.

4.1 Calculation of criteria weights with the FF-AHP method

In this study, expert input played a critical role across several stages of the methodology. First, experts contributed to identifying the key criteria that influence the resilience of supply networks under climate uncertainty. Next, their evaluations guided the development of a hierarchical structure, helping to determine the relative importance of these criteria. Finally, expert feedback was used to interpret and validate the results within the context of sustainable supply chain management. A rigorous selection process was applied to ensure the validity and reliability of the expert contributions. Experts were selected based on criteria including a minimum of five years of relevant professional or academic experience, demonstrated expertise in supply chain management or related fields, active involvement in research or practice, and a strong publication record. Therefore, a panel of ten anonymous experts (E1–E10) was formed. Throughout the study, these experts participated in structured evaluations using linguistic terms, contributed to pairwise comparisons using the FF-AHP approach, supported the consistency and soundness of the decision framework, and constructed an alternative evaluation matrix. Their diverse backgrounds ensured that the resulting model was not only theoretically rigorous but also grounded in practical relevance. The involvement of this panel significantly enhanced the robustness, transparency, and applicability of the proposed methodology for resilient and sustainable supply network design.

The panel comprises ten anonymous experts (academics, senior industry practitioners, and policy/risk consultants), selected using minimum experience ($\geq$ 5 years), domain expertise, and active scholarly/industrial engagement criteria. We apply the FFW operator at the

judgment level to aggregate judgments, which preserves inter-expert heterogeneity without forcing consensus. Conflicts in opinions are thus resolved statistically via aggregation rather than ad-hoc override; additionally, we monitor CI/CR per expert and request clarification only when CR exceeds the 0.10 threshold (none did). While we adopt equal expert weighting ex-ante to avoid subjective privileging, we also conduct robustness checks with non-uniform weights. Specifically, Sect. 4.2's sensitivity analysis includes randomized expert-weight scenarios (Table 9).

To enable a robust comparison of the main evaluation criteria, input was obtained from a panel of domain experts using a predefined set of linguistic terms (as shown in Table 2). Based on these assessments, PCMs were constructed for each expert, and the complete set of PCMs is presented in Table 5.

As an illustration, the PCM provided by Expert 1 in Table 5 can be interpreted as follows: The diagonal elements are all marked as E (Equal importance), since each criterion is compared with itself. According to Expert 1, C1 (Environmental Sustainability) is considered equally important as C2 (Climate Resilience), but significantly more important than C3 (Socioeconomic Factors), reflected by the VH (Very High Importance) rating. Similarly, Expert 1 judges C2 as very high (VH) in importance compared to C3, assigning it a VH value. These comparisons indicate that Expert 1 prioritizes environmental and climate-related dimensions over socioeconomic aspects.

Next, the consistency ratios for each expert's PCM were calculated to verify the reliability of their judgments, with the results summarized in Table 6. Once confirmed that all matrices met the acceptable consistency thresholds, the AHP procedure was executed to derive the final weight values for the main criteria**.**

FF-AHP was utilized to determine the relative importance of the main criteria for selecting the most suitable supply network strategy under climate change. The methodology was rigorously applied following all procedural steps, assigning equal weighting to each expert's input. Expert evaluations were aggregated by leveraging the FF-AHP approach to derive consistent and structured priority values. These values were then used to calculate the final weights of the main criteria, forming the basis for a comprehensive multi-criteria assessment of strategic alternatives. The main criteria weights are obtained as 0.362, 0.342, and 0.297 for Environmental Sustainability, Climate Resilience, and Socioeconomic Factors, respectively.

Following the determination of weights for the main (Level-1) criteria, the evaluation process proceeds with assessing the Level-2 criteria nested under each main criterion. This step is conducted using the same panel of experts, who provide their judgments via pairwise comparisons. The resulting Level-2 PCMs for each expert are presented in Table 7. These PCMs are then analyzed using the FF-AHP methodology to calculate the relative weights of the Level-2 criteria.

Subsequently, Level-3 comparisons are conducted to evaluate the sub-criteria associated with each Level-2 criterion. The corresponding Level-3 PCMs, derived from expert input, are provided in Table 11 (see Appendix).

As shown in Table 6, all PCMs for the Level-3 sub-criteria meet the required consistency threshold. The final weights and rankings of each Level-3 criterion are presented in Table 8.

Table 12 presents the final weights and rankings of Level-2 and Level-3 criteria used to evaluate supply network strategies under climate change. At the Level-2 tier, Environmental Impact holds the highest importance (0.1311), followed closely by Resource Efficiency (0.1256) and a tie between Climate Vulnerability and Climate Adaptation Investment (each 0.1206). Conversely, Community Impact ranks lowest (0.0909), suggesting a lesser role in strategic decision-making. At Level-3, Hazardous Material Usage (0.0470), Energy Efficiency (0.0466), and Pollution & Waste Generation (0.0442) emerge as the most influential

Table 5 Level-1 PCMs (E1–E10) for main criteria; linguistic judgments mapped from Table 2

	C1	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**
	E1			E2			E3			E4			E5		
C1	E	E	VH	E	VH	VH	E	H	VH	E	E	L	E	H	MH
C2	E	E	VH	VL	E	E	L	E	MH	E	E	L	L	E	ML
C3	VL	VL	E	VL	E	E	VL	ML	E	H	H	E	ML	MH	E
	E6			E7			E8			E9			E10		
C1	E	H	ML	E	ML	H	E	L	MH	E	ML	**H**	E	E	VH
C2	L	E	VL	MH	E	EH	H	E	EH	MH	E	**VH**	E	E	VH
C3	MH	VH	E	L	EL	E	ML	EL	E	L	VL	**E**	VL	VL	E

Table 6 Consistency ratios (CR) of expert PCMs across levels; CR ≤ 0.10 indicates acceptable consistency

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Level-1 Criteria	0	0	0.068	0	0.04	0.068	0.03	0.03	0.068	0
Level-2 of C1	0	0	0.03	0.056	0.068	0.084	0.068	0.068	0	0
Level-2 of C2	0	0.068	0.04	0.04	0	0.084	0.068	0.03	0	0.013
Level-2 of C3	0	0.068	0.03	0.04	0.084	0.068	0	0.068	0.068	0.013
Level-3 of C11	0	0.04	0	0.04	0.04	0.03	0.04	0	0.03	0
Level-3 of C12	0	0.03	0.03	0	0	0.068	0.084	0.068	0.068	0.084
Level-3 of C13	0.04	0.007	0	0	0.068	0.04	0.084	0.04	0.084	0
Level-3 of C21	0	0.068	0	0.03	0.04	0.007	0.03	0.068	0.04	0
Level-3 of C22	0	0.068	0.068	0.03	0.04	0.068	0.084	0.03	0.04	0.084
Level-3 of C23	0	0	0	0	0.084	0.068	0.084	0	0.04	0.013
Level-3 of C31	0	0	0.084	0.03	0	0	0.04	0.007	0	0
Level-3 of C32	0	0	0	0.04	0.03	0.04	0.03	0	0.084	0
Level-3 of C33	0	0	0	0.068	0	0.068	0.03	0.03	0.03	0

sub-criteria, emphasizing the strong weight placed on environmental and operational sustainability. In contrast, criteria such as Waste-to-Energy Practices, Flexibility of Infrastructure, and Stakeholder Engagement & Acceptance received lower weights, indicating they are relatively less critical in prioritizing supply strategies. These results highlight a clear preference for strategies that minimize environmental harm and improve resource utilization, reinforcing the central role of sustainability in climate-responsive supply chain planning. Recognizing potential composition effects, with academics emphasizing Policy Alignment and practitioners Operational Cost, we interpret the weight structure as a balanced synthesis of these perspectives. The FFW-based aggregation of consistent PCMs ensures no single subgroup dominates, so the final rankings reflect a consensus view across the panel.

Table 7 Level-2 PCMs for each main criterion (C1–C3) provided by experts (E1–E10)

	C11	C12	C13	C11	C12	C13	C11	C12	C13	C11	C12	C13	C11	C12	C13
	E1			E2			E3			E4			E5		
C11	E	H	E	E	MH	E	E	H	E	E	ML	E	E	H	VH
C12	L	E	L	ML	E	ML	L	E	ML	MH	E	MH	L	E	MH
C13	E	H	E	E	MH	E	E	MH	E	E	ML	E	VL	ML	E
	E6			E7			E8			E9			E10		
C11	E	VL	MH	E	VL	ML	E	VH	H	E	VH	VH	E	E	E
C12	VH	E	EH	VH	E	H	VL	E	ML	VL	E	E	E	E	E
C13	ML	EL	E	MH	L	E	L	MH	E	VL	E	E	E	E	E
	C21	C22	C23	C21	C22	C23	C21	C22	C23	C21	C22	C23	C21	C22	C23
	E1			E2			E3			E4			E5		
C21	E	E	H	E	L	MH	E	ML	MH	E	ML	MH	E	MH	MH
C22	E	E	H	H	E	VH	MH	E	H	MH	E	H	ML	E	E
C23	L	L	E	ML	VL	E	ML	L	E	ML	L	E	ML	E	E
	E6			E7			E8			E9			E10		
C21	E	VH	ML	E	ML	H	E	H	MH	E	ML	E	E	E	VH
C22	VL	E	EL	MH	E	VH	L	E	E	MH	E	MH	E	E	E
C23	MH	EH	E	L	VL	E	ML	E	E	E	ML	E	VL	E	L

Table 7 (continued)

	C31	C32	C33	C31	C32	C33	C31	C32	C33	C31	C32	C33	C31	C32	C33
	E1			E2			E3			E4			E5		
C31	E	H	H	E	L	MH	E	L	MH	E	MH	H	E	ML	VH
C32	L	E	E	H	E	VH	H	E	EH	ML	E	MH	MH	E	EH
C33	L	E	E	ML	VL	E	ML	EL	E	L	ML	E	VL	EL	E
	E6			E7			E8			E9			E10		
C31	E	VH	H	E	E	L	E	VH	H	E	H	VH	E	E	VL
C32	VL	E	ML	E	E	L	VL	E	ML	L	E	MH	E	E	L
C33	L	MH	E	H	H	E	L	MH	E	VL	ML	E	VH	H	E

Table 8 Local and final weights with ranks for Level-2 and Level-3 criteria computed via FF-AHP

Level 2 Criteria	Local weight	Final weight	Rank	Level 3 Criteria	Local weight	Final weight	Rank
Environmental impact	0.3627	0.1311	1	Pollution & Waste generation	0.3370	0.0442	3
				Biodiversity & Habitat preservation	0.3043	0.0399	12
				Hazardous material usage	0.3587	0.0470	1
Resource efficiency	0.3472	0.1256	2	Energy efficiency	0.3709	0.0466	2
				Water usage	0.3417	0.0429	5
				Material conservation	0.2873	0.0361	17
Climate mitigation	0.2902	0.1049	6	Renewable energy integration	0.3926	0.0412	8
				Waste-to-energy practices	0.2557	0.0268	26
				Low-emission logistics	0.3517	0.0369	15
Climate vulnerability	0.3530	0.1206	3	Exposure to extreme weather	0.3419	0.0412	7
				Time to recover from disruptions	0.3319	0.0400	11
				Backup resources	0.3262	0.0393	13
Climate adaptation investment	0.3530	0.1206	3	Infrastructure upgrades	0.3584	0.0432	4
				Monitoring systems	0.3084	0.0372	14
				Emergency preparedness & Training	0.3332	0.0402	10
Technological flexibility	0.2940	0.1005	7	Digitalization & Automation	0.4049	0.0407	9
				Innovation Capability	0.2980	0.0299	23
				Flexibility of infrastructure	0.2971	0.0299	25
Economic cost	0.3581	0.1062	5	Logistic cost	0.3922	0.0417	6
				Operational cost	0.2816	0.0299	24

Table 8 (continued)

Level 2 Criteria	Local weight	Final weight	Rank	Level 3 Criteria	Local weight	Final weight	Rank
				Investment cost	0.3262	0.0346	18
Policy alignment	0.3356	0.0995	8	Carbon policy compliance	0.3706	0.0369	16
				Environmental standards & Certifications	0.3141	0.0313	22
				Reporting & Transparency	0.3153	0.0314	21
Community impact	0.3063	0.0909	9	Local community welfare	0.3790	0.0344	19
				Job creation & Fair labor practices	0.3498	0.0318	20
				Stakeholder engagement & Acceptance	0.2712	0.0246	27

4.2 Ranking alternatives with the FF-WISP method

Each expert evaluates the set of alternative strategies (see Fig. 2) using the predefined criteria listed in Table 12 (see Appendix). To operationalize the ranking stage, we carry forward the FF-AHP weights obtained for all Level-3 criteria (Table 8) and apply the FF-WISP procedure to the expert evaluations reported in Appendix Table 12. The resulting FFN-based decision matrices are then aggregated using the FFW operator, assuming each expert has equal weight, ensuring a consistent and unified representation of expert opinions. Specifically, for each criterion j, expert FFN ratings are aggregated via the FFW operator (Eq. 10) and defuzzified using the score function (Eq. 8) to obtain crisp performances. These are combined with the FF-AHP weights to compute WSM/WPM values by criterion type (benefit or cost; Eqs. 15–18). Subsequently, both WSM and WPM values are computed for each alternative. These values serve as the basis for calculating the utility scores associated with each option. The remaining steps of the proposed methodology are then executed. We then derive the four utility measures (Eqs. 19–22), normalize them (Eqs. 23–26), and compute the overall utility for each alternative (Eq. 29), as illustrated in Fig. 3.

Figure 3 presents the evaluated supply network strategies' final utility scores, highlighting each alternative's performance under the proposed FF–AHP–FF–WISP framework. Among the four strategies, Hybrid (Global + Local) with Flexible Logistics emerges as the most effective option with a normalized score of 1.000, indicating its superior adaptability and robustness in managing climate-related supply chain challenges. Closely following is Regional Sourcing & High-Resilience Investment with a score of 0.993, reflecting strong performance, particularly in resilience and environmental adaptability. The Multiple Global Suppliers & Moderate Safety Stock strategy scored 0.939, suggesting moderate flexibility and risk mitigation benefits. Lastly, Single Global Sourcing & Lean Inventory received the lowest score (0.922), reflecting its limited responsiveness and higher vulnerability due to centralized sourcing and minimal inventory buffers. These results underscore the strategic

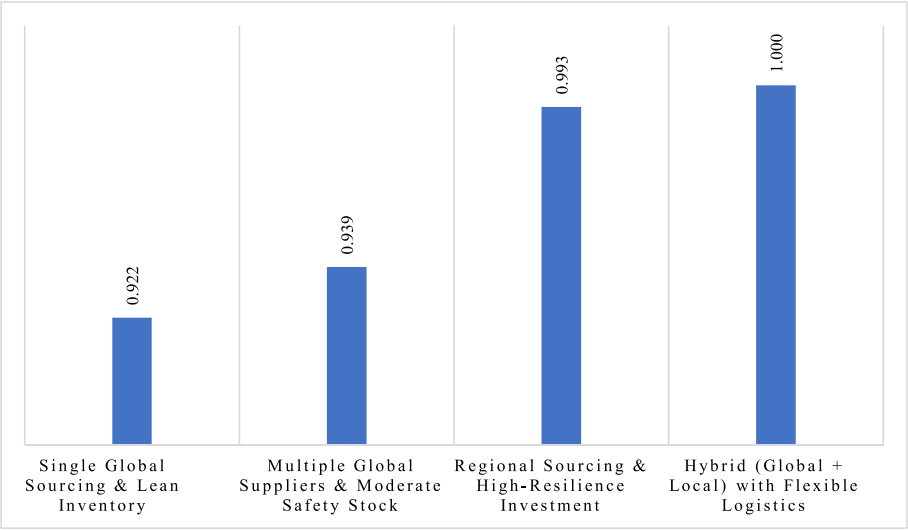


Fig. 3 Final utilities of S1–S4 obtained by FF-WISP using FF-AHP weights; higher utility indicates a more preferable supply network under mixed benefit–cost criteria

value of diversified sourcing and logistical flexibility in enhancing the sustainability and reliability of supply networks under climate uncertainty.

4.3 Sensitivity analysis

A sensitivity analysis was performed to evaluate the robustness and stability of the ranking outcomes. This analysis involved generating ten randomized expert weight sets to observe how variations in expert judgment could impact the prioritization of supply network strategies within the FF-WISP framework. The specific configurations of these weight sets are presented in Table 9.

Table 9 Ten randomized expert-weight sets (rows) used in sensitivity analysis

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Set-1	0.019	0.049	0.14	0.14	0.066	0.072	0.098	0.245	0.081	0.089
Set-2	0.121	0.12	0.125	0.118	0.099	0.092	0.149	0.006	0.123	0.047
Set-3	0.18	0.052	0.122	0.052	0.167	0.106	0.14	0.08	0.062	0.039
Set-4	0.003	0.03	0.119	0.092	0.233	0.041	0.064	0.274	0.08	0.065
Set-5	0.014	0.138	0.08	0.141	0.059	0.122	0.013	0.116	0.137	0.18
Set-6	0.109	0.065	0.123	0.183	0.049	0.186	0.035	0.004	0.217	0.029
Set-7	0.139	0.005	0.072	0.01	0.005	0.188	0.244	0.056	0.16	0.12
Set-8	0.084	0.068	0.115	0.004	0.18	0.061	0.112	0.145	0.127	0.105
Set-9	0.163	0.011	0.218	0.006	0.233	0.016	0.01	0.175	0.123	0.044
Set-10	0.028	0.1	0.148	0.101	0.088	0.084	0.153	0.013	0.091	0.195

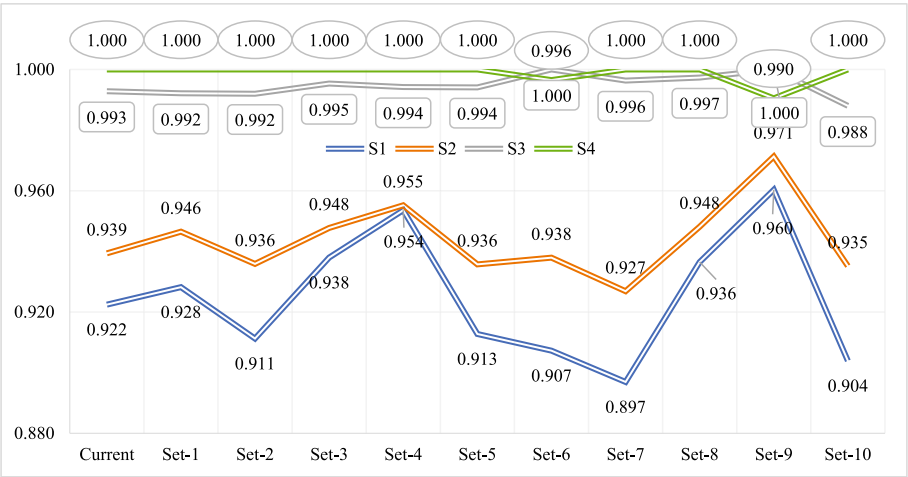


Fig. 4 Sensitivity analysis results: utilities of S1–S4 across ten randomized expert-weight sets

Subsequently, the FF-WISP methodology was re-executed using the criteria weights derived from the FF-AHP process across each of the ten randomly generated weight sets. The corresponding strategy rankings for each scenario are illustrated in Fig. 4.

The results presented in the table reflect the impact of varying expert weight sets on the final utility scores of the four strategic alternatives using the FF-WISP method. Across all ten simulated scenarios, Hybrid (Global + Local) with Flexible Logistics (S4) consistently achieves the highest score, either maintaining a perfect score of 1.000 or only slightly decreasing (as seen in Set-6 and Set-9), reinforcing its position as the most robust and favorable strategy under climate-related uncertainties. Similarly, Regional Sourcing & High-Resilience Investment (S3) also demonstrates strong performance, with scores ranging between 0.988 and 1.000, suggesting its stability as a top-tier strategy across a variety of weighting conditions.

In contrast, Single Global Sourcing & Lean Inventory (S1) and Multiple Global Suppliers & Moderate Safety Stock (S2) exhibit greater sensitivity to changes in expert weights, with S1's scores ranging from 0.897 to 0.960 and S2 from 0.927 to 0.971. While both still perform well, these fluctuations indicate a relatively higher dependence on specific weighting schemes. Overall, the sensitivity analysis confirms the robustness of the proposed ranking framework, particularly the dominance of hybrid and regionally resilient strategies in enhancing supply chain sustainability and adaptability in the face of climate change.

4.4 Comparative analysis

To benchmark the proposed FF-AHP–FF-WISP framework, we re-evaluated four alternatives using three established fuzzy MCDM methods (FF-TOPSIS, Ertugrul Ayyildiz & Erdogan, 2024), FF-VIKOR (Gül, 2021) and FF-CODAS (Bouraima et al., 2024)) with the same criteria weights and expert aggregation. As shown below, all methods produce an identical ranking: S4 (Hybrid) > S3 (Regional) > S2 (Multiple Global) > S1 (Single Global). Table 10 presents the rankings obtained from the different methods.

First, rank concordance is perfect (Spearman $\rho = 1$, Kendall $\tau = 1$), demonstrating that our hybrid approach is not method-dependent. Second, while the degree of separation between top

Table 10 Results of comparative analysis

	FF-WISP (↑ better)	FF-TOPSIS (↑ better)	FF-VIKOR (↓ better)	FF-CODAS (↑ better)
Single global sourcing & lean inventory	0.922	0.581	1.000	- 0.860
Multiple global suppliers & moderate safety stock	0.939	0.626	0.899	- 0.207
Regional sourcing & high-resilience investment	0.993	0.811	0.408	0.281
Hybrid (Global + Local) with flexible logistics	1.000	0.844	0.000	0.785

alternatives varies by method (e.g., the S4–S3 gap is 0.007 in WISP, 0.033 in TOPSIS, 0.408 in VIKOR, and 0.504 in CODAS), the ordering remains unchanged. This cross-method stability indicates that the preference for diversified, flexible configurations (S4) and regionally resilient designs (S3) is structurally supported by both additive–multiplicative aggregation (WISP) and distance/compromise-based logics (TOPSIS, CODAS, VIKOR). Conversely, S1 consistently ranks last, reflecting its higher vulnerability and limited adaptability; S2 is consistently intermediate. Overall, the comparative evidence substantiates our claim that FF-AHP–FF-WISP yields intuitive, transparent results in line with widely used fuzzy MCDM baselines, while retaining the modeling advantages of combined additive and multiplicative utilities.

5 Discussion

This study proposes scientific and robust results for ranking supply networks in the face of climate change. For this purpose, with the help of literature review and expert views, this paper offers 3-Level criteria sets. Level 1 represents Environmental Sustainability, Climate Resilience, and Socioeconomic Factors; the second level identifies Level-2 criteria, and the Level-3 identifies sub-criteria based on Level 2. Thus, alternative supply networks are evaluated under very comprehensive criteria using a novel hybrid MCDM methodology in this decision-making process.

The results show that the most important main criterion for this decision-making process is Environmental Sustainability. Among the nine sub-criteria in Level 2, the two most important criteria were determined as Environmental Impact and Resource Efficiency with 0.1311 and 0.1256 weights. The environmental impact criteria are divided into environmentally focused sub-criteria such as use of hazardous materials, pollution and waste production, and biodiversity and habitat preservation. Among the Level 3 sub-criteria, the first two most important sub-criteria were determined as Hazardous Material Usage and Pollution & Waste Generation. These criteria represent the negative impacts that may occur on the environment

as a result of supply network activities. Companies can improve their environmental performance by determining their supply chain strategies in a way that will reduce the negative impacts on the environment (Sabouhi et al., 2021). Furthermore, Climate Vulnerability and Climate Adaptation Investment were determined as the third most important criteria with equal weight values. The Infrastructure Upgrades criterion, which is linked to the Climate Adaptation Investment criterion, was determined as the fourth most important sub-criterion. This criterion refers to investment in physical improvements that protect the supply chain from climate risks. Among the 27 sub-criteria in Level 3, the least important one was determined to be Stakeholder Engagement & Acceptance, which is related to the Community Impact criterion. While each identified criterion is important for the supply network, this criterion was rated as less important than those with particularly high environmental impacts. Experts rated social impacts as less significant for this sector than criteria based on environmental and economic factors. These results emphasize that the activities and strategies of supply networks should be evaluated in the light of environmental and climatic criteria rather than social criteria. Mahmoud et al. (Mahmoud et al., 2024) emphasize the increasing interest in cleaner production technologies and environmental impact mitigation in supply chain management.

According to the ranking results of the alternatives, the supply networks are ranked from most important to least important as follows: *S4-S3-S2-S1*. According to this ranking, the best supply network strategy in light of the current criteria is determined as Hybrid (Global + Local) with Flexible Logistics Combining. All over the world, transportation infrastructure and logistics are becoming increasingly important as they become key factors affecting international trade (Shibasaki et al., 2021). Combining both global and local suppliers with adaptable logistics capabilities, this strategy offers operational flexibility. It responds quickly to disruptions by dynamically changing resources and routes, but it causes medium to high complexity and costs. Since the criteria are placed in order of importance, focusing on environmental and climate change adaptation rather than cost, this efficient strategy that provides operational flexibility is selected as the best alternative. Given the priority placed on environmental impact criteria, this alternative strategy stood out among others, particularly due to its prominence in these aspects, according to the numerous expert panels. Flexible logistics not only play an important role in achieving economic development, improving logistics efficiency, and increasing customer satisfaction, but also in ensuring efficient and flexible supply chain management (Tian et al., 2025). Therefore, while the costs may be high, the long-term benefits will be greater. In this respect, it promotes economic development. Experts have evaluated these alternative features as good in terms of efficient use of resources. The second important strategy is determined as Regional Sourcing & High-Resilience Investment. This approach uses suppliers closer to the target markets, accompanied by significant investment in climate-resilient infrastructure and operations. However, it provides high resilience against climate disruptions but requires substantial upfront investments. Li et al., to highlight the importance of this issue, established an assessment framework for the vulnerability of industrial sectors to climate change by considering a large number of industrial firms in China and proposed approaches to reduce this vulnerability (Li et al., 2025). The Multiple Global Suppliers & Moderate Safety Stock strategy ranked third in this evaluation process. This strategy relies on multiple suppliers across different global regions, supported by moderate inventory buffers. Balancing cost efficiency and resilience reduces risk through supplier diversification but increases coordination complexity. As can be seen, these strategies present different advantages and disadvantages for the supply chain. Moreover, the least suitable strategy was determined to be Single Global Sourcing & Lean Inventory. This strategy involves sourcing primarily from one global supplier with minimal inventory to reduce costs. However, it is

highly vulnerable to climate disruptions due to dependency on a single location and limited safety stock. This strategy, which has less flexibility, has been evaluated by experts as more advanced and less compatible than hybrid options.

Our sensitivity exercises, including randomized and structured non-uniform expert weightings, show that the leading alternatives remain unchanged, indicating that the results are not artifacts of equal weighting and are robust to reasonable expert-aggregation schemes.

The results propose that while all of these supply networks contribute to sustainable development, decision-makers and managers should consider environmental impact, resource efficiency, climate vulnerability, and especially hazardous material usage, energy efficiency, pollution, and waste generation based on these criteria when evaluating and determining supply network strategy to confirm alignment with global sustainability goals and under climate mitigation conditions.

6 Conclusion

This study emphasizes the critical factors of evaluating the sustainable supply networks in the face of climate change. For this aim, it stresses that the optimization process of supply networks is important for more sustainable supply chain management, with a technique reinforced by organized and holistic evaluation frameworks. The innovative and new integration of FF-AHP and FF-WISP methods provides a robust framework for evaluating supply networks according to a comprehensive 3-Level criteria set.

The results highlight that the most vital factor in this decision-making process is Environmental Sustainability, and the most important sub-criteria are Hazardous Material Usage and Pollution & Waste Generation, which are based on this main criterion. The findings emphasize that in evaluating and ranking the supply network process under climate change conditions, governments and managers are guided through the assessment process using a wide range of criteria sets, mainly reducing negative environmental impact. Additionally, the proposed novel methodology suggests a systematic procedure that can be improved in various contexts. Moreover, this study significantly contributes to the literature on this progression by providing a comprehensive, systematic, and detailed analysis reflecting the connection between environmental sustainability and climate change conditions with supply network optimization. Thus, it fills the gap in this important area of the literature with a robust approach and provides a guide for both future studies and managers, governments, and policymakers.

Further work can expand the supply network optimization process by including smart logistics technology integration and renewable energy integration. This situation will produce a more comprehensive framework for decision-making and the evaluation process. Additionally, the proposed hybrid MCDM approach can be extended to other issues, such as logistic system management or smart cities activities, and the criteria can be differentiated according to these fields. These structures will further the pertinence and strength of the approach and contribute to universal efforts to expand the scope of sustainability developments.

Appendix 1

See Tables 11 and 12.

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Table 11 PCMs for Level-3 criteria

	E1			E2			E3			E4			E5		
Pollution & Waste Generation	E	H	E	E	MH	H	E	H	H	E	L	ML	E	MH	ML
Biodiversity & Habitat Preservation	L	E	L	ML	E	MH	L	E	E	H	E	MH	ML	E	L
Hazardous Material Usage	E	H	E	L	ML	E	L	E	E	MH	ML	E	MH	H	E
Energy Efficiency	E	H	H	E	L	MH	E	L	MH	E	MH	MH	E	E	MH
Water Usage	L	E	E	H	E	EH	H	E	EH	ML	E	E	E	E	MH
Material Conservation	L	E	E	ML	EL	E	ML	EL	E	ML	E	E	ML	ML	E
Renewable Energy Integration	E	H	MH	E	VH	MH	E	VH	VH	E	MH	MH	E	VH	MH
Waste-to-Energy Practices	L	E	ML	VL	E	ML	VL	E	E	ML	E	E	VL	E	L
Low-Emission Logistics	ML	MH	E	ML	MH	E	VL	E	E	ML	E	E	ML	H	E
Exposure to Extreme Weather	E	ML	ML	E	L	MH	E	L	E	E	H	EH	E	ML	MH
Time to Recover from Disruptions	MH	E	E	H	E	VH	H	E	H	L	E	MH	MH	E	H
Backup Resources	MH	E	E	ML	VL	E	E	L	E	EL	ML	E	ML	L	E
Infrastructure Upgrades	E	E	MH	E	E	MH	E	E	MH	E	H	H	E	VH	EH
Technology & Monitoring Systems	E	E	MH	E	E	MH	E	E	MH	L	E	E	VL	E	MH
Emergency Preparedness & Training	ML	ML	E	ML	ML	E	ML	ML	E	L	E	E	EL	ML	E
Digitalization & Automation	E	E	ML	E	H	ML	E	H	ML	E	H	MH	E	MH	ML
Innovation Capability	E	E	ML	L	E	VL	L	E	VL	L	E	E	ML	E	L
Flexibility of Infrastructure	MH	MH	E	MH	VH	E	MH	VH	E	ML	E	E	MH	H	E
Logistic Cost	E	E	E	E	VH	VH	E	VH	EH	E	H	MH	E	E	MH
Operational Cost	E	E	E	VL	E	E	VL	E	MH	L	E	E	E	E	MH
Investment Cost	E	E	E	VL	E	E	EL	ML	E	ML	E	E	ML	ML	E
Carbon Policy Compliance	E	E	ML	E	E	E	E	ML	E	E	ML	L	E	H	EH

Table 11 (continued)

	E1			E2			E3			E4			E5		
Environmental Standards & Certifications	E	E	ML	E	E	E	MH	E	MH	MH	E	ML	L	E	MH
Reporting & Transparency	MH	MH	E	E	E	E	E	ML	E	H	MH	E	EL	ML	E
Local Community Welfare	E	MH	E	E	MH	MH	E	MH	MH	E	MH	VH	E	L	E
Job Creation & Fair Labor Practices	ML	E	ML	ML	E	E	ML	E	E	ML	E	H	H	E	H
Stakeholder Engagement & Acceptance	E	MH	E	ML	E	E	ML	E	E	VL	L	E	E	L	E
	E6			E7			E8			E9			E10		
Pollution & Waste Generation	E	H	ML	E	MH	H	E	E	E	E	H	ML	E	VL	VL
Biodiversity & Habitat Preservation	L	E	EL	ML	E	MH	E	E	E	L	E	EL	VH	E	E
Hazardous Material Usage	MH	EH	E	L	ML	E	E	E	E	MH	EH	E	VH	E	E
Energy Efficiency	E	VH	H	E	EH	VH	E	VH	MH	E	H	ML	E	ML	E
Water Usage	VL	E	ML	EL	E	ML	VL	E	L	L	E	VL	MH	E	VH
Material Conservation	L	MH	E	VL	MH	E	ML	H	E	MH	VH	E	E	VL	E
Renewable Energy Integration	E	H	MH	E	EH	MH	E	H	MH	E	ML	VL	E	E	E
Waste-to-Energy Practices	L	E	ML	EL	E	VL	L	E	ML	MH	E	EL	E	E	E
Low-Emission Logistics	ML	MH	E	ML	VH	E	ML	MH	E	VH	EH	E	E	E	E
Exposure to Extreme Weather	E	MH	ML	E	H	EH	E	ML	VL	E	MH	ML	E	E	E
Time to Recover from Disruptions	ML	E	VL	L	E	MH	MH	E	L	ML	E	L	E	E	E
Backup Resources	MH	VH	E	EL	ML	E	VH	H	E	MH	H	E	E	E	E
Infrastructure Upgrades	E	VH	H	E	EH	MH	E	E	MH	E	MH	ML	E	E	VH
Technology & Monitoring Systems	VL	E	ML	EL	E	VL	E	E	MH	ML	E	L	E	E	H
Emergency Preparedness & Training	L	MH	E	ML	VH	E	ML	ML	E	MH	H	E	VL	L	E
Digitalization & Automation	E	L	MH	E	ML	VH	E	H	EH	E	H	MH	E	VH	ML

Table 11 (continued)

	E6			E7			E8			E9			E10		
Innovation Capability	H	E	VH	MH	E	EH	L	E	E	L	E	ML	VL	E	EL
Flexibility of Infrastructure	ML	VL	E	VL	EL	E	EL	E	E	ML	MH	E	MH	EH	E
Logistic Cost	E	E	MH	E	H	MH	E	VH	MH	E	E	L	E	E	L
Operational Cost	E	E	MH	L	E	ML	VL	E	ML	E	E	L	E	E	L
Investment Cost	ML	ML	E	ML	MH	E	ML	MH	E	H	H	E	H	H	E
Carbon Policy Compliance	E	MH	ML	E	H	VH	E	MH	MH	E	MH	EH	E	E	E
Environmental Standards & Certifications	ML	E	L	L	E	MH	ML	E	E	ML	E	VH	E	E	E
Reporting & Transparency	MH	H	E	VL	ML	E	ML	E	E	EL	VL	E	E	E	E
Local Community Welfare	E	VH	MH	E	MH	VH	E	H	EH	E	L	MH	E	ML	E
Job Creation & Fair Labor Practices	VL	E	L	ML	E	H	L	E	MH	H	E	EH	MH	E	MH
Stakeholder Engagement & Acceptance	ML	H	E	VL	L	E	EL	ML	E	ML	EL	E	E	ML	E

Table 12 Alternative evaluation matrices

	Expert-1				Expert-2				Expert-3				Expert-4				Expert-5			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Pollution & Waste Generation	G	MG	VG	G	EB	EB	EG	G	F	VG	EG	VG	MG	G	G	VG	VB	MB	G	MG
Biodiversity & Habitat Preservation	G	MG	VG	G	EB	EB	EB	G	F	EG	EG	VG	G	G	G	VG	VB	MB	G	G
Hazardous Material Usage	MG	MG	VG	G	MG	MB	EG	G	G	VG	EG	VG	G	G	G	VG	MB	F	G	G
Energy Efficiency	G	MG	G	G	MB	MG	MG	EG	MG	VG	VG	VG	VB	MB	MG	VG	VB	B	F	G
Water Usage	G	MG	G	G	MB	F	F	VG	B	VG	EG	VG	B	F	G	VG	MB	MB	F	G
Material Conservation	G	MG	G	G	MB	MG	MG	VG	G	VG	VG	VG	F	F	G	VG	MB	MB	F	G
Renewable Energy Integration	G	G	G	G	MB	MG	F	VG	G	EG	EG	EG	F	MG	MG	MG	G	MG	B	MB
Waste-to-Energy Practices	G	G	G	G	MB	MG	MG	VG	G	VG	VG	VG	B	F	G	MG	G	MG	B	MB
Low-Emission Logistics	G	G	VG	G	VG	MB	EB	MB	VG	VG	VG	VG	B	F	G	MG	EB	B	EG	VG

Table 12 (continued)

	Expert-1				Expert-2				Expert-3				Expert-4				Expert-5			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Exposure to Extreme Weather	MG	MG	G	G	F	MG	MG	VG	B	MG	G	VG	EB	B	MG	VG	VB	F	MG	MG
Time to Recover from Disruptions	G	MG	G	VG	EB	VG	G	EG	G	G	VG	VG	EB	B	F	VG	EB	MB	G	EG
Backup Resources	G	MG	G	VG	VB	VG	G	VG	VB	MG	EG	VG	EB	B	F	VG	EB	VB	MG	VG
Infrastructure Upgrades	G	G	G	VG	B	F	F	G	MB	G	VG	G	MB	F	G	VG	G	MG	B	F
Monitoring Systems	VG	G	G	G	VG	MB	G	MB	G	VG	MG	F	VG	G	F	F	G	MG	B	F
Emergency Preparedness & Training	G	G	VG	VG	EB	VG	G	EG	MG	EG	MB	G	VG	VG	F	B	MG	MG	B	MG
Digitalization & Automation	MG	VG	G	G	B	F	F	G	VG	EG	G	VG	G	G	F	B	EG	VG	B	MB
Innovation Capability	MG	VG	VG	G	EB	VG	G	EG	VG	EG	MG	MG	MG	G	G	VG	EG	VG	B	MB
Flexibility of Infrastructure	MG	VG	VG	VG	B	MG	F	VG	G	VG	VG	VG	B	F	G	VG	G	G	B	G
Logistic Cost	VG	VG	MB	MB	VB	B	EG	VB	G	G	VG	G	B	F	G	VG	F	MG	EG	VG
Operational Cost	VG	VG	MB	F	EB	VB	G	VG	G	G	VG	G	EB	F	G	VG	EG	G	EB	B
Investment Cost	VG	G	B	F	MB	MB	MB	F	G	G	VG	G	B	F	G	VG	EG	VG	EB	B
Carbon Policy Compliance	G	G	G	G	F	F	F	F	EG	G	B	G	B	F	MG	G	EG	G	B	MB

Table 12 (continued)

	Expert-1				Expert-2				Expert-3				Expert-4				Expert-5			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Environmental Standards & Certifications	G	G	G	G	F	F	F	F	EG	G	B	G	MB	F	MG	G	EG	G	B	MB
Reporting & Transparency	VG	G	G	VG	F	F	F	F	EG	EG	G	G	B	F	MG	G	EG	G	B	MB
Local Community Welfare	G	G	G	G	EB	EB	EG	G	VG	VG	EG	VG	B	MB	MG	G	MB	F	EG	VG
Job Creation & F Labor Practices	MG	VG	VG	VG	EB	EB	EG	G	VG	EG	EG	EG	B	MB	G	VG	B	MB	EG	VG
Stakeholder Engagement & Acceptance	G	G	G	G	VB	VB	F	VG	G	G	G	G	B	MB	G	VG	EG	VG	MB	F
	Expert-6				Expert-7				Expert-8				Expert-9				Expert-10			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Pollution & Waste Generation	B	F	VG	G	EB	MB	EG	VG	VG	G	MG	F	F	MG	G	G	F	G	G	VG
Biodiversity & Habitat Preservation	VB	F	VG	G	B	VB	EG	G	EG	VG	G	MG	B	F	MG	MG	G	G	VG	VG

Table 12 (continued)

	Expert-6				Expert-7				Expert-8				Expert-9				Expert-10			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Hazardous Material Usage	MB	F	G	F	B	VB	VG	G	VG	G	MG	F	MB	MG	G	VG	MB	MB	VG	VG
Energy Efficiency	VG	G	G	VG	MB	B	G	MG	VG	G	MG	F	F	G	VG	G	MB	F	F	EG
Water Usage	B	F	VG	G	VB	EB	G	G	G	MG	F	MB	F	MG	EG	G	MB	G	G	G
Material Conservation	G	G	VG	VG	VB	B	G	VG	F	F	F	F	MB	G	VG	MG	F	G	G	G
Renewable Energy Integration	VB	MB	VG	VG	B	MB	VG	EG	MG	F	MB	MB	MB	F	G	VG	F	G	G	G
Waste-to-Energy Practices	B	F	VG	G	B	VB	G	VG	VG	G	MG	F	B	MG	G	G	MB	MB	VG	VG
Low-Emission Logistics	EB	MB	VG	G	VB	VB	VG	EG	VG	MG	F	F	VB	MB	VG	G	G	G	G	G
Exposure to Extreme Weather	EB	F	VG	G	EB	B	MG	VG	F	G	EG	VG	EB	F	VG	G	MB	G	VG	VG
Time to Recover from Disruptions	VB	F	VG	VG	EB	F	MG	VG	F	G	VG	EG	EB	MG	EG	VG	G	G	G	G
Backup Resources	B	G	VG	VG	VB	MG	G	EG	F	G	VG	EG	VB	MG	VG	G	MB	F	G	VG
Infrastructure Upgrades	VB	F	EG	G	VB	B	F	G	MB	F	G	VG	B	MG	EG	VG	G	G	G	G

Table 12 (continued)

	Expert-6				Expert-7				Expert-8				Expert-9				Expert-10			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Monitoring Systems	B	F	VG	VG	B	MB	MG	EG	MB	F	G	VG	B	G	VG	G	G	G	G	G
Emergency Preparedness & Training	VB	F	VG	VG	B	F	MG	VG	F	G	VG	EG	B	G	VG	VG	MB	F	G	VG
Digitalization & Automation	F	F	VG	VG	VB	G	B	VG	F	F	F	F	MB	G	VG	EG	G	G	G	G
Innovation Capability	F	G	VG	VG	EB	VG	VB	G	F	F	F	F	F	MG	VG	EG	G	G	G	G
Flexibility of Infrastructure	VB	F	VG	EG	VB	MG	B	G	VG	G	MG	F	VB	MG	G	EG	MB	F	G	VG
Logistic Cost	VG	G	VB	F	B	MG	G	VG	G	F	VG	F	G	MG	B	MB	MB	F	G	VG
Operational Cost	VG	G	VB	MB	B	MG	MG	G	F	F	F	F	VG	G	MB	F	MB	F	G	VG
Investment Cost	VG	G	VB	MB	VG	G	B	F	G	VG	MB	F	EG	G	EB	B	MB	F	G	VG
Carbon Policy Compliance	B	F	VG	VG	B	F	VG	MG	F	F	F	F	B	G	VG	G	G	G	G	G
Environmental Standards & Certifications	B	F	VG	VG	MB	MG	VG	VG	F	F	F	F	MB	G	EG	VG	G	G	G	G
Reporting & Transparency	MB	F	VG	VG	VB	MG	VG	EG	F	F	F	F	F	MG	VG	VG	G	G	G	G
Local Community Welfare	VB	F	EG	VG	VB	B	G	G	F	F	MG	G	F	MG	EG	VG	G	G	G	G

Table 12 (continued)

	Expert-6				Expert-7				Expert-8				Expert-9				Expert-10			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Job Creation & F Labor Practices	B	F	VG	VG	B	MG	EG	G	F	F	MG	G	MB	G	VG	VG	MB	F	G	VG
Stakeholder Engagement & Acceptance	MB	F	VG	VG	B	B	G	EG	F	F	MG	G	MB	G	EG	VG	G	G	G	G

Declarations

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

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