

Optimizing Carbon Emission Mitigation Strategies Using Hesitant Fuzzy Methodology

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Abstract

Optimizing carbon emission mitigation strategies is critical for balancing economic growth and environmental sustainability in cities like Kahramanmaraş, Türkiye. This study employs Hesitant fuzzy multi-criteria decision-making (HF-MCDM) techniques to evaluate and prioritize strategies based on environmental, economic, and social criteria. Kahramanmaraş, known for its industrial activities in metal kitchenware, textiles, and agriculture, faces unique challenges and opportunities in achieving carbon reduction targets. This research aligns with Türkiye's commitments under the Paris Agreement, providing policymakers with a structured framework to identify the most effective and feasible strategies for sustainable development. More specifically, the study addresses the complexity of urban carbon mitigation planning under uncertainty by incorporating hesitant fuzzy evaluations into the decision-making process, thereby capturing the ambiguity and subjectivity inherent in expert judgments. In doing so, it develops a context-sensitive prioritization framework for a city characterized by energy-intensive production, rapid urban development, and increasing climate vulnerability. The proposed approach not only identifies the most suitable mitigation strategies, but also reveals the relative importance of environmental protection, economic feasibility, and social acceptance in local climate action planning. The findings offer practical implications for urban planners, local authorities, and industrial stakeholders by supporting more transparent, systematic, and robust policy design. In addition, the study contributes to the literature by demonstrating how hesitant fuzzy methodology can enhance strategic carbon mitigation assessments in medium-sized industrial cities facing multidimensional sustainability challenges.

Keywords

Carbon Emission Mitigation, Hesitant Fuzzy Multi-Criteria Decision-Making, Sustainable Development, Environmental Management, Carbon Reduction Strategies

1. Introduction

Kahramanmaraş is located between 37-38 degrees north latitude and 36-37 degrees east longitude. The city center lies at an altitude of 568 meters above sea level, with its northern regions being significantly mountainous. The organization of urban spaces inherently determines the flow of urban energy. Therefore, the integration of urban spatial

planning with energy flow planning is one of the most critical (and simultaneously most vulnerable) tools available to local governments in combating climate change (Bibri, 2022).

The world is said to be under the threat of the Water-Food-Energy Nexus—a triple helix whose combined impacts are far greater than the sum of its parts due to their synergistic interactions. At the heart of this nexus lie cities. The Mediterranean Basin, which includes Turkey, is among the most vulnerable regions globally to climate change. A 2°C increase in temperature in the Mediterranean Basin would manifest as extreme weather events, heatwaves, an increase in the frequency and intensity of wildfires, droughts, and consequently, loss of biodiversity, declines in tourism revenue, agricultural yield reductions, and, most critically, water scarcity (Karabulut et al., 2019).

The Climate Change National Action Plan, published in 2011, predicts that the annual average temperature in Turkey will rise by 2.5°-4°C in the coming years, with increases reaching 4°C in the Aegean and Eastern Anatolia regions and up to 5°C in the interior (Türkiye, 2024). It foresees a hotter, drier, and more unpredictable climate in terms of precipitation in the near future. All plans devised for Kahramanmaraş must account for these changes.

Planning and implementing strategies to reduce the city's energy and carbon intensities are among the foremost measures needed to create a sustainable and livable city. Measures to mitigate the destructive effects of climate change cannot be separated from actions such as adopting low-carbon options in transportation and the built environment or using local renewable energy (Lu and Lu, 2024). Collectively, these measures contribute to creating healthier cities—enhancing air, water, and soil quality—while also serving as essential components in preparing for disasters.

To effectively mitigate carbon emissions in Kahramanmaraş, strategies must be tailored to the city's unique environmental, economic, and social dynamics. Given its industrial profile, which includes energy-intensive sectors, and its expanding urban development, a multi-faceted approach is essential. Urban planning must prioritize integrating renewable energy sources and low-carbon technologies, particularly in industrial zones and new residential areas. Furthermore, the social fabric of Kahramanmaraş, characterized by tight-knit communities, provides an opportunity for grassroots initiatives such as public awareness campaigns, community-driven renewable energy projects, and improved public transportation systems. These strategies not only reduce emissions but also foster local engagement, economic resilience, and environmental stewardship.

To systematically evaluate and prioritize these mitigation strategies, the Hesitant Fuzzy Multi-Criteria Decision-Making (HF-MCDM) approach, particularly the Analytic Hierarchy Process (AHP), can provide a robust framework. This methodology allows stakeholders to account for the inherent uncertainty and hesitation in decision-making by weighing diverse criteria—such as environmental impact, economic feasibility, and social acceptance—against each other. By applying AHP, DMs can optimize carbon emission mitigation strategies, ensuring that solutions align with Kahramanmaraş's complex industrial profile, urbanization patterns, and community dynamics. This approach ensures a balanced and sustainable path forward, leveraging both quantitative analysis and qualitative insights to address the city's pressing environmental challenges (Liu and Rodríguez, 2014).

The steps involved in our analysis can be described as follows: Define the Alternatives and Criteria: List strategies (alternatives) and define measurable criteria. Weight the Criteria: Assign importance to each criterion based on stakeholder preferences or expert input. Evaluate Alternatives: Score each alternative against the criteria. Rank the Alternatives: Use Proposed MCDM techniques like AHP to prioritize the strategies.

This study begins by identifying the critical criteria and sub-criteria required for optimizing carbon emission mitigation strategies in Kahramanmaraş, focusing on environmental, economic, and social dimensions. These criteria are assessed using the Hesitant Fuzzy Analytic Hierarchy Process (HF-AHP) to address uncertainties and subjective judgments inherent in decision-making. Subsequently, a prioritization of mitigation strategies is conducted based on their performance against these criteria, allowing for a systematic evaluation of alternatives. The findings are then validated through sensitivity and comparative analyses to ensure the robustness and consistency of the prioritization

process. Finally, the study concludes by highlighting the most effective carbon emission mitigation strategies for Kahramanmaraş and discussing their implications for urban planning, industrial policy, and community engagement.

2. Carbon emission mitigation strategies

Carbon emission mitigation strategies for Kahramanmaraş, based on environmental, economic, and social criteria, should address the city's industrial profile, urban development, and community dynamics. Combining these strategies across criteria ensures holistic progress. For instance, deploying renewable energy (environmental) with subsidies (economic) while creating jobs (social) aligns with all three pillars. Prioritizing strategies can be facilitated using a HF-MCDM framework to evaluate their effectiveness comprehensively. In an MCDM research, alternatives are the potential options or strategies being evaluated, while criteria are the parameters or factors used to assess and compare these alternatives (Büyüközkan and Göçer, 2018). Here's the set of Alternatives and Criteria for our research on carbon emission mitigation in Kahramanmaraş.

2.1 Alternatives (Mitigation Strategies):

These are specific strategies to reduce carbon emissions based on the context of Kahramanmaraş as seen in Table 1.

Table 1. Alternatives (Mitigation Strategies)

Alternative	Definition
Renewable Energy Adoption (A_1)	Encourage the use of solar, wind, and hydroelectric energy, leveraging Kahramanmaraş's geographical advantages for renewable energy generation (Zhao et al., 2024).
Energy Efficiency Programs (A_2)	Promote energy-efficient technologies and retrofitting in industries, especially in metal kitchenware and textile manufacturing (Bharti et al., 2024).
Sustainable Transportation Development (A_3)	Expanding public transportation and promoting electric vehicle use (Bharti et al., 2024; Zhao et al., 2024).
Waste-to-Energy Conversion (A_4)	Convert municipal and industrial waste into bioenergy, reducing landfill emissions (Tan et al., 2014).
Afforestation and Urban Greening (A_5)	Implement large-scale afforestation projects and green urban spaces to act as carbon sinks (Kuhn et al., 2025).
Circular Economy Models (A_6)	Encourage recycling and resource optimization in production processes, particularly in textiles and metal industries (Chandrani et al., 2025; Mohsin et al., 2024).

2.2 Criteria (environmental, economic, and social)

These are the factors against which each alternative is evaluated based on environmental, economic, and social pillars as seen in Table 2.

Table 2. Criteria (environmental, economic, and social)

Criteria	Definition
Environmental Criteria (C_1)	Strategies focusing on reducing the carbon footprint and enhancing ecological sustainability
Emission Reduction Potential (C_{11})	The amount of CO ₂ or equivalent emissions reduced by the strategy (Bharti et al., 2024; Kuhn et al., 2025; Zhao et al., 2024).
Ecological Impact (C_{12})	The strategy's effect on biodiversity and local ecosystems (Bharti et al., 2024; Zhao et al., 2024).
Resource Efficiency (C_{13})	Efficient use of natural resources such as water, energy, and land (Bharti et al., 2024; Kuhn et al., 2025; Zhao et al., 2024).
Economic Criteria (C_2)	Strategies aiming to be cost-effective while fostering economic growth

Green Industry Incentives (C_{21})	Provide tax breaks or subsidies to industries adopting cleaner production techniques or renewable energy (Bharti et al., 2024; Tan et al., 2014).
Low-Carbon Transport (C_{22})	Develop efficient public transportation systems and promote electric vehicles with infrastructure support (Bharti et al., 2024; Chandrani et al., 2025; Tan et al., 2014).
Carbon Credit Systems (C_{23})	Participate in carbon trading markets to generate economic benefits from emission reductions (Chandrani et al., 2025; Tan et al., 2014).
Support for SMEs (C_{24})	Offer financial and technical support to small and medium-sized enterprises transitioning to sustainable practices (Chandrani et al., 2025; Tan et al., 2014).
Social Criteria (C_3)	Strategies to ensure public acceptance and community benefits
Public Acceptance (C_{31})	The likelihood of community support and engagement. Raise awareness about climate change and carbon reduction through workshops and campaigns (Bharti et al., 2024; Chandrani et al., 2025; Mohsin et al., 2024).
Employment in Green Sectors (C_{32})	Create job opportunities in renewable energy, waste management, and sustainable agriculture (Chandrani et al., 2025; Mohsin et al., 2024).
Equity and Inclusiveness (C_{33})	Ensure that mitigation measures do not disproportionately affect low-income or vulnerable groups (Kuhn et al., 2025; Sandy Thomas, 2009).
Participatory Decision-Making (C_{34})	Engage stakeholders, including local communities, in the planning and implementation of mitigation strategies (Chandrani et al., 2025; Mohsin et al., 2024).
Health and Wellbeing Improvements (C_{35})	Reduce air pollution from industrial emissions to improve public health outcomes (Bharti et al., 2024; Chandrani et al., 2025; Mohsin et al., 2024).

3. Proposed Methodology

3.1 Preliminaries of the Hesitant Fuzzy Linguistic Term Set (HFLTS)

The complexity inherent in real-world decision-making often stems from the uncertainty surrounding the available alternatives. One method to address this uncertainty is the use of linguistic information. However, decision-making becomes increasingly challenging when experts must choose between multiple criteria in the absence of sufficient information. The HF-MCDM approach leverages comparative hesitant fuzzy linguistic term sets (HFLTS) to uncover insights in situations of hesitation. This approach is particularly suitable for scenarios where the information provided is incomplete. Hesitant fuzzy sets (HFS), originally introduced by Torra (2010), are fundamental to this method.

In the context of HFSs, an element's degree of membership may take on multiple possible values within the range of zero to one. This characteristic makes HFS a powerful tool for articulating hesitation during evaluation, and as a result, it has gained widespread adoption among researchers dealing with high levels of uncertainty. Liu and Rodriguez (2014) proposed an MCDM model in which decision-makers (DMs) expressed their evaluations through linguistic terms structured as HFLTS.

Let X represent a set. An HFS is a function and a subset of $[0, 1]$, formally defined as follows (Torra, 2010):

$$E = \{ \langle x, h_E(x) \rangle \mid x \in X \}$$

$\mathbf{M} = \{\mu_1, \mu_2, \dots, \mu_n\}$ represents a set of n membership functions. An HFS associated with $\mathbf{M}$, denoted $\mathbf{h}_M$, is described:

$$h_M: M \rightarrow \{[0, 1]\}$$

$$h_M(x) = \bigcup_{\mu \in M} \{\mu(x)\}$$

A linguistic term set, S , is defined as $S = \{s_0, \dots, s_g\}$. An HFLTS, H_s , is an ordered finite subset of the sequential terms within S . The function E_{GH} maps expressions in natural language to HFLTS, H_s . The grammar G_H utilizes the linguistic term set S , generating an expression domain S_{ll} . The mapping is represented as:

$$E_{GH}: S_{ll} \rightarrow H_s$$

Using this approach, comparative linguistic expressions are converted into HFLTS as follows:

$$\begin{aligned} E_{GH}(s_i) &= \{s_i | s_i \in S\} \\ E_{GH}(\text{at most } s_i) &= \{s_j | s_j \in S \text{ and } s_j \leq s_i\} \\ E_{GH}(\text{less than } s_i) &= \{s_j | s_j \in S \text{ and } s_j < s_i\} \\ E_{GH}(\text{at least } s_i) &= \{s_j | s_j \in S \text{ and } s_j \geq s_i\} \\ E_{GH}(\text{greater than } s_i) &= \{s_j | s_j \in S \text{ and } s_j > s_i\} \\ E_{GH}(\text{between } s_i \text{ and } s_j) &= \{s_k | s_k \in S \text{ and } s_i \leq s_k \leq s_j\} \end{aligned}$$

The envelope of an HFLTS, denoted $env(H_s)$, is a linguistic interval bounded by H_{s-} (lower bound) and H_{s+} (upper bound), expressed as:

$$env(H_s) = [H_{s-}, H_{s+}], H_{s-} \leq H_{s+}$$

The use of linguistic expressions in this framework offers two primary advantages. First, the incorporation of hesitant linguistic terms simplifies the decision-making process, enabling DMs to express their evaluations more flexibly. Second, the approach offers a broad range of linguistic alternatives due to its inherent elasticity, as noted by prior studies (Büyüközkan and Güler, 2020; Camci et al., 2018; Zhu et al., 2016).

This adaptability preserves the natural characteristics of the expressions, making HFLTS particularly suitable for complex scenarios with numerous influencing factors. For instance, selecting optimal strategies in health tourism, which involves evaluating a multitude of criteria, demonstrates the utility of this method (Çevik Onar et al., 2016; Zhu et al., 2016).

3.2 Hesitant Fuzzy Analytic Hierarchy Process (HF-AHP)

The AHP is a structured decision-making framework developed by Thomas L. Saaty in the 1970s (Saaty, 1977). It helps in evaluating and prioritizing multiple alternatives based on a set of criteria by breaking the decision problem into a hierarchy. AHP involves pairwise comparisons of criteria and alternatives, allowing DMs to assign relative importance using a consistent numerical scale. These comparisons generate a priority matrix, and eigenvalue methods are used to calculate weights that reflect the relative importance of each element. AHP is widely used in diverse fields like business, engineering, and healthcare for making complex decisions in a transparent and logical manner.

The HF-AHP is an advanced decision-making method used to evaluate and prioritize options when there is uncertainty or hesitation in linguistic assessments (Rodriguez et al., 2012).

Below is the step-by-step methodology, along with the mathematical operations involved.

1. Define the Problem and Objectives

- Clearly identify the decision problem and its objectives.
- Determine the criteria and sub-criteria that influence the decision.
- Establish alternatives that need to be evaluated.

2. Construct the Hierarchical Structure

Create a hierarchical model with:

- Level 1: The overall goal (e.g., selecting the best option).
- Level 2: Criteria affecting the goal ($C_i, i = 1, 2, \dots, m$).
- Level 3: Sub-criteria (if applicable). ($C_{ij}, i = 1, 2, \dots, m, j = 1, 2, \dots, n$)
- Level 4: Alternatives ($A_l, l = 1, 2, \dots, s$).

Step 3: Collect Hesitant Fuzzy Linguistic Preferences

- Define linguistic terms: Use linguistic variables (e.g., "very important," "moderately important") to express preferences.
- Represent Hesitant Fuzzy Linguistic Elements (HFLEs):
- HFLEs are sets of possible linguistic terms, each mapped to a hesitant fuzzy number:

$$\tilde{H}_{ij} = \{h^1_{ij}, h^2_{ij}, \dots, h^k_{ij}\}$$

where h^k_{ij} represents the kth linguistic value in the hesitant set for comparison of criteria i and j.

Table 3. Linguistic scale for HF-AHP

Linguistic terms	s_i	Abb.	a	b	c
Definitely low important	s0	DLI	0.11	0.11	0.14
Extremely low important	s1	EXLI	0.11	0.14	0.20
Essentially low important	s2	ESLI	0.14	0.20	0.33
Weakly low important	s3	WLI	0.20	0.33	1.00
Equally low important	s4	ELI	0.33	1.00	1.00
Exactly low important	s5	EE	1.00	1.00	1.00
Equally high important	s6	EHI	1.00	1.00	3.00
Weakly high important	s7	WHI	1.00	3.00	5.00
Essentially high important	s8	ESHI	3.00	5.00	7.00
Extremely high important	s9	EXHI	5.00	7.00	9.00
Definitely high important	s10	DHI	7.00	9.00	9.00

Not: a, b, and c represent the lower, modal, and upper values of the triangular fuzzy numbers

- Incorporate hesitation: Allow DMs to express multiple possible linguistic terms for a single comparison. For instance, between two criteria, a DM might state both "important" and "very important."
- Represent these preferences using HFLEs:
- Conversion of Linguistic Terms to Numerical Scale:
 - Table 3 defines a numerical scale for linguistic terms (Çevik Onar et al., 2016).

Step 4: Construct Pairwise Comparison Matrices

- Develop pairwise comparison matrices for each level of the hierarchy using HFLEs.
- Create the Pairwise Comparison Matrix:
 - Represent the pairwise comparisons of criteria using hesitant fuzzy sets:

$$A = \begin{bmatrix} \tilde{H}_{11} & \cdots & \tilde{H}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{H}_{n1} & \cdots & \tilde{H}_{nn} \end{bmatrix}$$

Diagonal elements ($\tilde{H}_{ii}$) are $\tilde{H}_{ii} = \{1\}$.

- Each matrix compares criteria (or sub-criteria) relative to their importance toward the parent node in the hierarchy.

Example of pairwise comparisons for criteria C_1 and C_2 : HFLE: {"Moderately Important", "Very Important"}

Operations on HFLEs:

- Hesitant Fuzzy Addition: Combine hesitant sets element-wise (Zhang and Chen, 2020):

$$\tilde{H}_1 + \tilde{H}_2 = \{h^k_1 + h^k_2 | h^k_1 \in \tilde{H}_1, h^k_2 \in \tilde{H}_2\}$$

- Hesitant Fuzzy Multiplication:

$$\tilde{H}_1 \times \tilde{H}_2 = \{h^k_1 \times h^k_2 | h^k_1 \in \tilde{H}_1, h^k_2 \in \tilde{H}_2\}$$

Step 5: Determine Hesitant Fuzzy Linguistic Weights

- Aggregate group judgments: Combine individual HFLEs into a group decision using aggregation operators (e.g., average operators for hesitant fuzzy sets) (Zhang and Chen, 2020).
 - Hesitant Fuzzy Weighted Average (HFWA):

$$\tilde{H}^{agg}_{ij} = \frac{1}{m} \sum_{p=1}^m \tilde{H}^p_{ij}$$

where m is the number of DMs, and $\tilde{H}^p_{ij}$ is the hesitant set provided by decision-maker p.

- Use normalization:
 - Normalize the hesitant fuzzy weights so they sum to 1:

$$W_i = \frac{\sum_{h \in \tilde{H}_i} h}{\sum_{j=1}^n \sum_{h \in \tilde{H}_j} h}$$

Step 6: Check Consistency

- Consistency Index (CI) for Hesitant Fuzzy Matrices:
-Calculate consistency using a hesitant fuzzy linguistic consistency ratio:

$$CR = \frac{CI}{RI}, \text{ where } CI = \frac{\lambda_{\max} - n}{n-1}$$

- RI is the random index for matrices of size n.
-Calculate $\lambda_{\max}$ by aggregating the normalized pairwise comparison matrix.
- Ensure the judgments are consistent; if not, revise the pairwise comparisons.

Step 7: Synthesize to Obtain Priority Weights

- Calculate the global priority weights for each criterion and alternative by combining local weights from different levels of the hierarchy.
-For alternatives $A_1, A_2, \dots, A_l$ calculate the global weight for each alternative:

$$W_{global}(A_l) = \sum_{j=1}^n (C_j) \times W_{alternative}(A_l|C_j)$$

- Apply hesitant fuzzy linguistic aggregation to handle hesitation and linguistic uncertainty (Zhang and Chen, 2020).
-Defuzzify the hesitant fuzzy numbers to a crisp value:

$$\text{Defuzzification}(\tilde{H}) = \frac{\sum_{h \in \tilde{H}} h}{|\tilde{H}|}$$

- Rank the alternatives based on their defuzzified values.

4. Application

The proposed methodology steps were systematically applied, incorporating the multi-criteria decision-making framework to assess carbon emission mitigation strategies for Kahramanmaraş. Mitigation alternatives, including 1 (Renewable Energy Adoption (A_1)), 2 (Circular Economy Models (A_6)), 3 (Energy Efficiency Programs (A_2)), 4 (Sustainable Transportation Development (A_3)), 5 (Waste-to-Energy Conversion (A_4)), and 6 (Afforestation and Urban Greening (A_5)), were prioritized in the specified order based on their performance against environmental, economic, and social criteria. Sensitivity and comparison analyses, as depicted in Figure 1, were conducted to ensure the robustness and reliability of the rankings, providing a comprehensive evaluation framework for sustainable urban planning in the region (Table 4-Table 5).

Table 4. Linguistic judgments for HFL AHP

C	11	12	13	21	22	23	24	31	32	33	34	35
11	s5	s3	s4	s2	s4	s5	s6	s4	s3	s5	s8	s7
12		s5	s9	s8	s9	s7	s4	s2	s3	s6	s7	s4
13			s5	s3	s3	s5	s4	s6	s7	s5	s1	s7
21				s5	s0	s3	s2	s5	s2	s4	s0	s6
22					s5	s9	s10	s8	s7	s8	s2	s10
23						s5	s4	s4	s5	s3	s3	s3
24							s5	s2	s1	s1	s4	s7
31								s5	s2	s2	s1	s6
32									s5	s7	s7	s8
33										s5	s6	s10
34											s5	s8
35												s5

Table 5. HFL Scores

Alternatives	HFL Score			Crisp Score	Priority
(A_1)	0.202	0.397	0.759	0.452	1
(A_2)	0.142	0.286	0.578	0.335	3
(A_3)	0.173	0.320	0.452	0.315	4
(A_4)	0.098	0.193	0.395	0.228	5

(A ₅)	0.066	0.123	0.243	0.144	6
(A ₆)	0.238	0.411	0.652	0.433	2

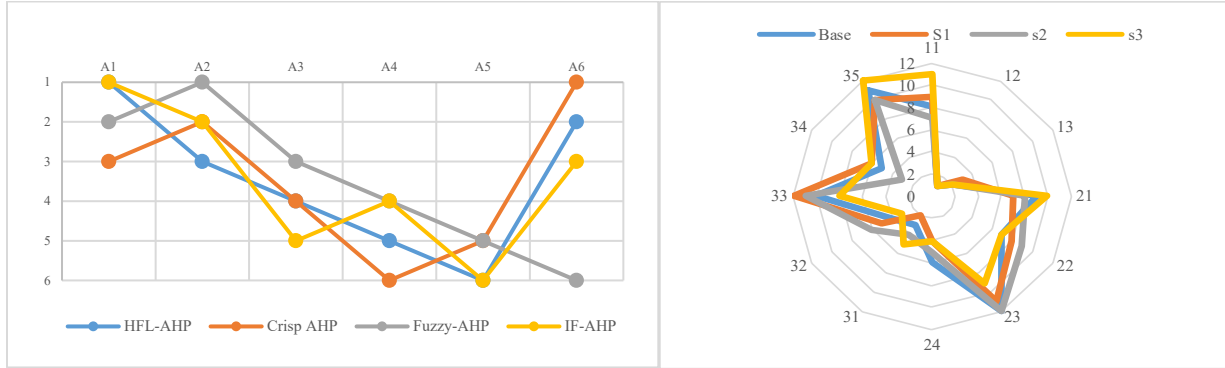


Figure 1. Sensitivity and Comparison of HFL-AHP

The results obtained from the HF-AHP analysis reveal significant differences among the proposed carbon emission mitigation strategies. As shown in Table 5, Renewable Energy Adoption (A1) achieved the highest crisp score (0.452) and was ranked as the most preferred strategy. This result highlights the importance of utilizing Kahramanmaraş's renewable energy potential, particularly solar and hydro resources, to achieve substantial carbon emission reductions while supporting long-term sustainability objectives.

Afforestation and Urban Greening (A6) ranked second with a crisp score of 0.433. This finding indicates that nature-based solutions play a critical role in carbon sequestration and environmental improvement. In addition to reducing atmospheric carbon concentrations, urban greening initiatives contribute to biodiversity conservation and public well-being.

Circular Economy Models (A2) and Energy Efficiency Programs (A3) ranked third and fourth, respectively. These strategies support resource optimization and reduce industrial energy consumption, which is particularly relevant for Kahramanmaraş's textile and metal manufacturing sectors. Their relatively high rankings demonstrate the importance of integrating cleaner production practices into local industrial development policies.

Sustainable Transportation Development (A4) and Waste-to-Energy Conversion (A5) received lower priority scores. Although these alternatives contribute to carbon reduction, experts perceived their implementation challenges, infrastructure requirements, and economic feasibility as relatively less favorable compared with the higher-ranked alternatives.

The sensitivity and comparative analyses presented in Figure 1 further confirm the robustness of the proposed HF-AHP framework. The ranking structure remains largely stable across different scenarios and alternative MCDM approaches, including classical AHP, Fuzzy-AHP, and IF-AHP. This consistency indicates that the obtained priorities are not highly sensitive to minor changes in parameter settings and expert judgments, thereby enhancing the reliability of the proposed decision-support model.

Overall, the findings suggest that policy makers in Kahramanmaraş should prioritize renewable energy investments and urban greening initiatives while simultaneously promoting circular economy practices and energy efficiency programs. Such an integrated approach would provide balanced environmental, economic, and social benefits, contributing to the city's long-term sustainability and climate resilience objectives.

5. Conclusion

This study effectively prioritized carbon emission mitigation strategies for Kahramanmaraş using a HF-MCDM approach, ensuring a balanced consideration of environmental, economic, and social criteria. Strategies such as renewable energy adoption, sustainable transportation, and circular economy models emerged as top priorities,

aligning with the city's unique industrial and urban dynamics. Sensitivity and comparative analyses validated the robustness of the rankings, offering a reliable framework for decision-making. By integrating these strategies, Kahramanmaraş can achieve sustainable development goals, enhance environmental quality, and foster economic resilience, providing a replicable model for addressing climate challenges in similar urban contexts.

Beyond identifying the priority strategies, this study also demonstrates the value of hesitant fuzzy methodology in addressing uncertainty, vagueness, and expert hesitation in urban sustainability planning. In this respect, the proposed framework provides not only a ranking mechanism, but also a decision-support structure that can assist local governments in designing more coherent and context-specific climate policies. For Kahramanmaraş, where industrial production, urban growth, and environmental pressures intersect, such a structured approach is especially important for balancing emission reduction goals with economic continuity and social feasibility.

The results indicate that carbon mitigation should not be treated as an isolated environmental agenda, but rather as a multidimensional urban transformation process involving energy systems, transportation planning, industrial adaptation, and community participation. Accordingly, the prioritization of renewable energy, sustainable transportation, and circular economy practices reflects the need for integrated policy interventions capable of generating both environmental and socio-economic co-benefits. These strategies have the potential to improve air quality, strengthen resource efficiency, reduce long-term climate risks, and enhance the resilience of the local economy.

Another important contribution of the study lies in its methodological relevance. By combining hesitant fuzzy logic with multi-criteria evaluation, the research offers a practical and transferable model for other cities facing similar climate, industrial, and governance challenges. Therefore, the framework may serve as a replicable tool for municipalities and regional decision-makers seeking to formulate evidence-based carbon mitigation roadmaps under uncertainty.

Nevertheless, the study is subject to certain limitations. The findings are based on a specific set of criteria, expert evaluations, and a local case context, which may influence the generalizability of the results. Future studies may expand the analysis by incorporating broader stakeholder groups, dynamic data sources, scenario-based assessments, or longitudinal evaluations. Furthermore, integrating HF-MCDM with artificial intelligence, big data analytics, and spatial decision-support systems could enhance the adaptability and real-time policy relevance of future carbon mitigation research.

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