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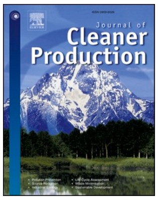

A novel intuitionistic fuzzy decision-making framework for sustainable site selection of solar panel waste recycling facilities

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ABSTRACT

Increasing global energy demand makes the transition to efficient and clean energy sources, such as solar energy, necessary. However, decommissioned solar panels generate hazardous waste, creating significant environmental challenges. Establishing an optimal location for solar panel waste recycling facilities is crucial to ensuring sustainability and compliance with environmental regulations. This study identifies and evaluates a detailed set of criteria, including environmental, economic, social, and technical aspects, critical for the site selection of solar panel waste recycling plants. This study offers the first methodical approach for solar waste management in Türkiye, confirming that growing solar energy investments align with sustainable waste treatment strategies. To handle the complexities of this process, an integrated methodology combining an improved Intuitionistic Fuzzy Indifference Threshold-Based Attribute Ratio Analysis (IF-ITARA) and Intuitionistic Fuzzy Evaluation based on Distance from Average Solution (IF-EDAS) is proposed. IF-ITARA is developed and introduced to the literature to provide a more precise determination of criteria weights, while IF-EDAS ranks the five potential sites in Turkiye, including Izmir, Konya, Kayseri, Antalya, and Sanliurfa, based on these weights. This approach effectively manages uncertainties and subjectivity in decision-making by incorporating intuitionistic fuzzy logic, providing a robust and systematic evaluation. The findings show that the most significant factor in the site selection process of the solar panel waste recycling plant is the legal and regulatory environment. The results offer valuable insights for policymakers and stakeholders involved in solar waste management and sustainable infrastructure planning. This study not only advances the application of decision-making approaches but also contributes to the broader goal of promoting a circular economy in the renewable energy sector.

1. Introduction

Reliable, efficient and environmentally friendly solar is a renewable form of energy and proposes many advantages (Xu et al., 2018). Solar energy contributes substantially to global energy consumption. Therefore, solar energy is an abundant and green energy source that can completely replace traditional energy sources in the near future and is the center of renewable energy sources (Hamukwaya et al., 2022). Also, while CO_2 emissions caused by electricity generated with fossil fuels are between 400g and 1000g per kWh, CO_2 emissions from silicon-based solar panels are insignificant (Louwen et al., 2015). One way to convert solar energy into a tangible energy source is to use solar panels, which are also known as photovoltaic modules, solar cells, or solar electric panels (Khalil et al., 2023). As energy consumption rises with increasing human activities, interest in renewable energy sources, including solar energy, is accelerating (Maghraby et al., 2025).

Today, it causes environmental pollution through the emission of gases that threaten human health, the leaching of heavy metals that pollute soil and groundwater, and the inadequate utilization of valuable materials found in used solar panels (Chiang et al., 2024). However, once solar panels reach their useful lifespan, they become hazardous waste, which poses an environmental problem (Xu et al., 2018). In Türkiye, according to the Regulation on the Control of Waste Electrical and Electronic Equipment, end-of-life photovoltaic solar panels are explicitly classified as hazardous waste if they contain dangerous substances or exceed certain concentration limits, in line with Annexes III

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and IV of the regulation (TC Ministry of Environment and Urban Development, 2012). Accordingly, the management, handling, and recycling of waste solar panels must fully comply with the legal requirements and environmental protection standards set by Turkish authorities. This regulatory framework ensures that hazardous characteristics are properly addressed, and the recycling process adheres strictly to both environmental safety and public health principles in Türkiye. If the panels are not processed effectively, hazardous wastes are formed due to heavy metals such as lead, cadmium and arsenic used in panel production (Ngagoum Ndalloka et al., 2024). Toxic heavy metals such as cadmium and lead are called hazardous waste because they have negative effects on living things and the environment. Additionally, toxic heavy metals such as cadmium and lead, which make up less than 1 % of solar panels, sink into residue from recycling, causing the residue to be classified as hazardous waste (Xu et al., 2018). Despite the long life of solar cells, waste is a global concern due to the expiration of some solar systems recently and the inadequacy of disposing of panel materials in an environmentally friendly manner (Yu et al., 2022). For this reason, the importance of solar panel waste recycling plants is increasing worldwide. Suitable solar panel waste recycling plant site selection is the foundation for sustainable solar energy development and renewable energy activities. Although there are site selection studies on waste recycling plants in the literature, a strong study such as this one, which addresses the solar panel waste recycling plants site selection process under a comprehensive set of criteria and with the proposed new hybrid multi-criteria decision-making (MCDM) approach, is lacking. Although mathematical model-based approaches have been developed for waste recycling (Liu et al., 2019; Shen et al., 2024; Shi et al., 2019; Xu et al., 2017), MCDM approaches have also been preferred (Ayyildiz and Erdogan, 2023; Kumar et al., 2020; Mishra et al., 2024; Rafiquee et al., 2024; Sherif et al., 2022; Soto-Paz et al., 2023; Zhang et al., 2025). For example, fuzzy-based decision-making methods such as Fuzzy AHP and Fuzzy COPRAS, which are widely used in other site selection problems, have been preferred. Nevertheless, a solid structure is needed for the site selection of solar panel waste recycling plants. Therefore, this study fills an important gap in the literature. The site selection process involves determining a wide set of criteria and evaluating the most suitable alternative according to these criteria. The criteria and alternatives must be determined correctly, especially in sensitive issues where environmental impact is at the forefront. There are various factors in the recycling process, such as land destruction, environmental pollution, and hazards caused by heavy metals (Ngagoum Ndalloka et al., 2024). In addition, despite its usefulness, the solar panel recycling process faces challenges such as a lack of research and analysis support and information on the subject, a lack of economic incentives, and complex laws and policies (Curtis et al., 2021; Ngagoum Ndalloka et al., 2024).

As a developing country with growing energy demands and the conditions to benefit from efficient solar panels, Türkiye should ensure that waste recycling facilities for these panels are appropriately determined to ensure the sustainability of the solar panels it uses intensively and make them more compatible with the environmental conditions. This research aims to fill the gap in the existing literature by presenting a novel MCDM methodology for choosing the most suitable location for solar panel waste recycling facilities in Türkiye.

This research aims to highlight the comprehensive criteria set and choose the most suitable waste recycling plant location for solar panels. The criteria were identified through an extensive literature review and experts' views, confirming a comprehensive evaluation framework. To achieve this purpose, the study introduces a novel MCDM approach, integrating the Intuitionistic Fuzzy Indifference Threshold-Based Attribute Ratio Analysis (IF-ITARA) and Intuitionistic Fuzzy Evaluation based on Distance from Average Solution (IF-EDAS) methods for evaluating alternative locations. This integration methodology addresses the uncertainty and complexity inherent in decision-making processes, resulting in a robust site selection assessment for solar panel recycling plants tailored to urban contexts under a sustainable perspective. Additionally, this study addresses the essential uncertainties in the decision-making process and is exclusive in its capability to assess the solar panel waste recycling plant site selection for Türkiye in light of numerous criteria sets.

While numerous studies have investigated waste recycling facility site selection, relatively few specifically focus on the optimal location of photovoltaic waste recycling plants. Recent works, such as those by Zhang et al. (2025) and Rafiquee et al. (2024), explored this problem using various multicriteria methods. However, these studies primarily employed conventional fuzzy methodologies, thus creating a gap regarding the comprehensive integration of technical, economic, environmental, and social criteria within an intuitionistic fuzzy framework. Additionally, traditional MCDM approaches and their fuzzy extensions frequently lack robustness in effectively managing uncertainties, capturing expert subjectivity, and addressing the complex trade-offs inherent in decision-making processes (Sadiq and Tesfamariam, 2009). In contrast, IFSs allow simultaneous modeling of membership, non-membership, and hesitation degrees, providing a more realistic representation of expert judgments (Tavana et al., 2016). Furthermore, the IF-ITARA method has not yet been applied within this domain, limiting the accuracy and precision of criteria weighting in prior studies. This research bridges these methodological gaps by proposing a novel integrated framework combining IF-ITARA and IF-EDAS, specifically tailored for Türkiye. The proposed approach significantly enhances robustness and precision by effectively incorporating ambiguity and expert hesitancy within a comprehensive sustainability-oriented assessment.

Despite Türkiye's high solar energy potential and growing adoption of solar power, there is a lack of a structured framework to determine optimal locations for solar panel waste recycling facilities. Existing national policies on renewable energy sustainability lack data-driven decision models for site selection.

The main contributions of the study to the literature are as follows.

- This research fills a critical gap by developing a structured methodology specifically for determining the optimal location for solar panel waste recycling plants, ensuring alignment with sustainability goals and circular economy principles.
- This study advances the IF-ITARA method by improving its capability to determine criteria weights in uncertain and complex decision environments.
- The integration of IF-ITARA and IF-EDAS for site selection is novel, offering a robust and systematic approach to ranking alternative locations under fuzzy uncertainty.
- Unlike previous studies, this research identifies and evaluates a detailed set of criteria covering environmental, economic, social, and technical aspects critical for solar panel waste recycling facility location selection.
- This study provides the first systematic approach for solar waste management in Türkiye, ensuring that growing solar energy investments align with sustainable waste treatment strategies.

Section 2 reviews the waste recycling plants' site selection. Section 3 proposes the IF-ITARA and IF-EDAS methods to determine the criteria weights and scores of the alternative locations. Section 4 proposes a case study for selecting the site of the solar panel waste recycling plant. Section 5 investigates the results and offers conclusions and directions for future work.

2. Literature review

Studies in the field of waste management and related waste recycling are becoming increasingly widespread (Akoredeley et al., 2022; Al-Raqeb et al., 2024; Al-Raqeb and Ghaffar, 2025a, 2025b). Although there are various works in the literature on this field, studies on site selection for these plants are limited. Some of these studies have solved their

Table 1
The summary of related works.

Reference	Problem	Method	Fuzzy sets	Criteria	Application area
Wu et al. (2016)	Waste-to-energy facility location selection	Cloud model	2-order additive fuzzy measures	Production, natural, environment, land, policy, social factors	China
Xu et al. (2017)	Site selection for coal gangue contamination recycling plants	GIS, bi-level model	Triangular fuzzy	Construction costs, capacity, and economic factors	China
Ayyildiz and Erdogan (2023)	Optimal site identification for organic waste collection and recycling facilities	CODAS, AHP with fuzzy interval type-2 sets	Fuzzy interval type-2 (T2F)	Economic, environmental, social, geographical, accessibility, climate—38 sub-criteria	Türkiye
Sherif et al. (2022)	Battery recycling plant location selection	Fuzzy AHP, fuzzy COPRAS	Triangular	Economic, technical, social, and environment,20 sub-criteria	India
Gomes et al. (2008)	Performance evaluation of waste recycling facilities	Multicriteria Decision Aiding Hybrid Algorithm	–	–	Brazil
Liu et al. (2019)	Construction and demolition (C&D) waste recycling facility site selection	Genetic algorithm, dual-objective planning model	–	Resident acceptance, environmental impact, cost	China
Shi et al. (2019)	Site selection for a construction and demolition waste recycling plant	Genetic algorithm, multi-objective location model	–	Amount of waste generated, costs, distances	China
Shen et al. (2024)	Optimal location problem for medical waste recycling	Multi-objective optimization model	–	Amount of waste generated, costs, loading reliability, travel time reliability, transportation risk	China
Kumar et al. (2020)	Location assessment for waste electrical and electronic equipment (WEEE) recycling plants	Best-Worst Method (BWM), VIsekriterijumska optimisacija i KOmpromisno Resenje (VIKOR)	–	Social, specialized, financial, natural, and political (STEEP)	India
Soto-Paz et al. (2023)	Site selection of construction and demolition waste facilities	GIS, F-AHP, TOPSIS	Triangular	Social, technical, economic—19 sub-criteria	Colombia
Mishra et al. (2024)	Site selection for household waste recycling plants	Fermatean Fuzzy- measurement alternatives and the ranking according to compromise solution (MARCOS), method with the removal effects of criteria (MEREC), stepwise weight assessment ratio analysis (SWARA)	Fermatean	Economic, social, environmental, risk—10 sub-criteria	India
Zhang et al. (2025)	Site selection for photovoltaic waste recycling centers	MULTIMOORA	Triangular	Economic, social, environmental—11 sub-criteria	China
Rafiquee et al. (2024)	Location selection of a photovoltaic waste recycling plant	Fuzzy Triangular Fuzzy Number (TFN), COPRAS	Triangular	Environmental, technical, economic, social—11 sub-criteria	India
Moharrami and Jalili Ghazizade (2025)	Evaluate the most effective MCDM methods for the optimal municipal solid waste landfill site	BWM, TOPSIS, AHP, Ordered weighted averaging (OWA), combined compromise solution (CoCoSo), weighted aggregates sum product assessment (WASPAS)	Linear	Distance based factors-27 criteria	Tehran
Güler and Altay (2025)	Location selection for waste electrical &electronic equipment recycling plant	SWARA, Additive Ratio Assessment (ARAS)	–	Environmental, legal and logistical, infrastructural, socio-economic factors—16 sub-criteria	Istanbul
Maden (2024)	Site selection for waste electrical &electronic equipment recycling plant	EDAS, Entrophy	–	Land availability, environmental concerns, economic feasibility, regulatory support, public perception—13 sub criteria	Türkiye
Kaya et al. (2020)	Location selection for waste electrical &electronic equipment recycling plant	Pythagorean fuzzy AHP	Pythagorean	Economic, environmental, social, risk—15 sub criteria	Istanbul
Feng et al. (2024)	Site selection for electric vehicle battery recycling transfer station	BWM, Cumulative prospect theory	–	Economic, social, environmental, technical, resilience—15 sub criteria	Company H
Puviarasu et al. (2023)	Evaluation of battery recycling plant location	BWM, TOPSIS, Fuzzy Decision making trial and evaluation laboratory (DEMATEL)	Triangular	socio-cultural, technical, environmental, economic, policy and legal—26 sub criteria	India
This study	*Solar panel waste recycling plant site selection*	*IF-ITARA, IF-EDAS*	*Intuitionistic*	*Social, economic, environmental, and technical—23 sub-criteria*	*Türkiye*

problems using various MCDM approaches (Ayyildiz and Erdogan, 2023; Gomes et al., 2008; Sherif et al., 2022). Ayyildiz and Erdogan (2023) applied the Analytical Hierarchy Process (AHP) and Combinative Distance-based Assessment (CODAS) with fuzzy interval type-2 sets methods for organic waste collection and recycling center location selection. In the study, six distinct areas were evaluated by considering 65 sub-criteria depending on six main criteria, and the ecological impact was emphasized as the most important factor in this decision process. Sherif et al. (2022) examined the location selection process for a battery recycling plant in India, identifying four primary criteria—social, economic, environmental, and technical—along with 23 sub-criteria. To evaluate and rank potential sites, they utilized the fuzzy COPRAS (Complex Proportional Assessment of Alternatives) and fuzzy AHP methods, ensuring a comprehensive and structured decision-making approach. In another study, the Multicriteria Decision Aiding Hybrid Algorithm (THOR) methodology was used in the performance evaluation process of waste recycling facilities. For this purpose, alternatives to plastic waste destinations were evaluated. The benefits of this approach, such as eliminating factors that do not impact the rating process, are emphasized (Gomes et al., 2008).

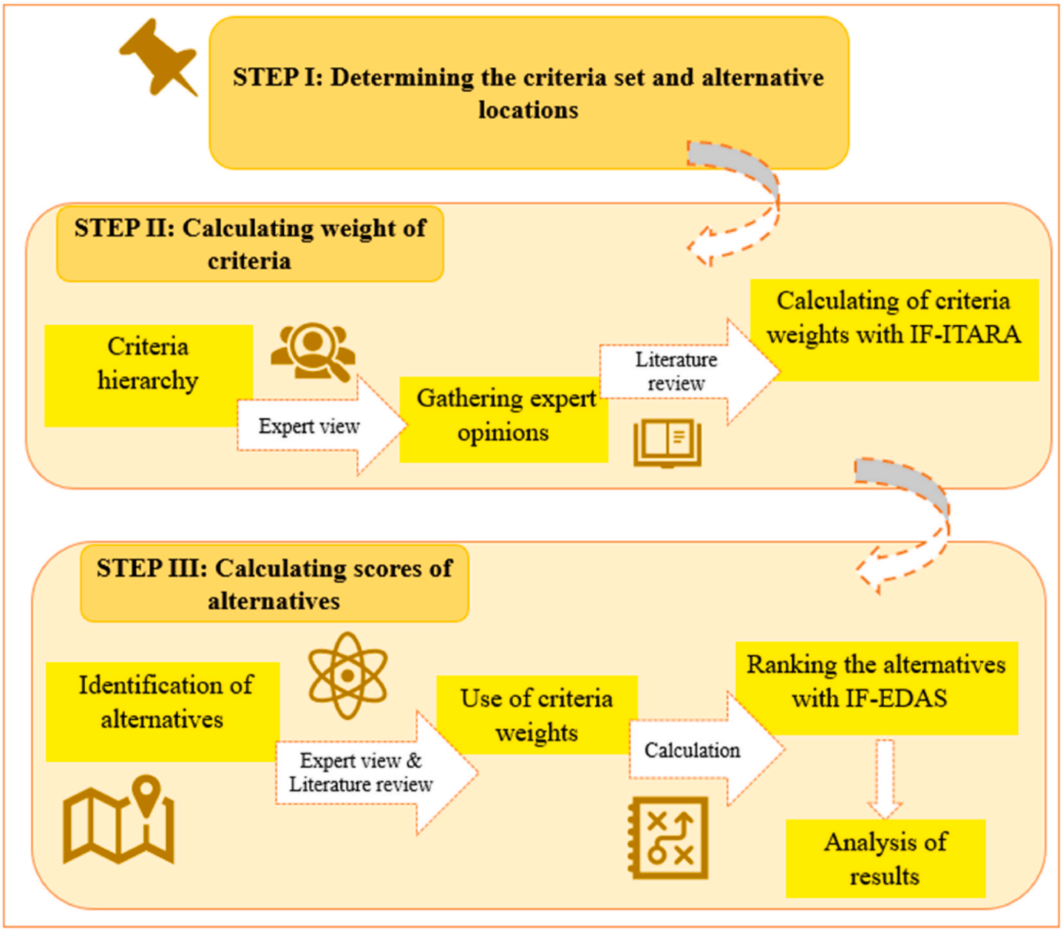

Fig. 1. Flowchart of the study.

Some studies have proposed mathematical models with genetic algorithms for the construction and demolition waste recycling plant site selection (Liu et al., 2019; Shi et al., 2019). Xu et al. (2017) proposed a Geographical Information System (GIS) and a bi-level model for the recycling facility site selection problem for coal gangue contamination. Alternative locations are identified with GIS, and the optimal location selection process is completed using the proposed model.

In this phase, the SCOPUS database was used to retrieve relevant articles, and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) background was followed to confirm a systematic literature review. This method was established by Moher et al. (2010). In this method, the first stage is to determine criteria, the second stage is to assess sources, and the third stage includes selecting suitable portions of literature. The last stage includes data gathering and selection of data fundamentals, respectively (Ayyildiz and Erdogan, 2023; Santi and Putra, 2018). In this study, the following keywords was used: *"solar panel waste" OR "waste recycling" OR "recycling plants" AND "site selection" OR "location selection" AND "multi-criteria" OR "mcdm" OR "mcda" OR "madm" OR "Multi-Objective Decision Making" OR "Multi--Criteria Decision Analysis" OR ahp OR topsis OR vikor OR codas OR waspas OR edas OR bwm OR aras OR saw OR swara OR fucom OR anp OR electre OR promethee OR moora OR multimoora OR copras OR dematel OR critic OR cocoso OR mabac OR "entropy method" OR "Analytic Hierarchy Process" OR "Technique for Order of Preference by Similarity to Ideal Solution" OR "Vise Kriterijumska Optimizacija I Kompromisno Resenje" OR "entropy method" OR "Combinative Distance-Based Assessment" OR "Weighted Aggregated Sum Product Assessment" OR "Evaluation Based on Distance from Average Solution" OR "Best-Worst Method" OR "Additive Ratio Assessment" OR "Simple Additive Weighting" OR "Step-wise Weight Assessment Ratio Analysis" OR "Full Consistency Method" OR "Analytic Network Process" OR "Elimination et Choice Translating Reality" OR "Preference Ranking Organization Method for Enrichment Evaluations" OR "Multi-Objective Optimization on the Basis of Ratio Analysis" OR "Complex Proportional Assessment" OR "Decision-Making Trial and Evaluation Laboratory" OR "Criteria Importance Through Intercriteria Correlations".*

As a result of this search, 23 documents were identified. Among these, those related to waste recycling site selection are summarized in Table 1.

Table 1 reveals that there are a limited number of waste recycling plant site selection studies in the literature. It is clear that there is a need for a site selection study with a solid and systematic approach in light of comprehensive criteria for solar panel waste recycling plants. For this important process, first of all, vital criteria must be determined by using a detailed literature review and expert opinions, and alternative locations must be evaluated with a robust approach in light of these criteria and from a sustainability perspective. Such a methodology will provide a guide for both other site selection problems and this research field. Addressing this gap requires a novel approach that considers numerous economic, environmental, technical, etc., criteria, and many sub-criteria associated with these criteria should be defined. This paper completes an analysis of the following hypotheses: (i) Sustainability approaches can be effectively integrated into the most suitable location selection process for solar panel waste recycling plants. (ii) The decision-making process is made more effective with the fuzzy-based hybrid framework proposed for this area. This study also strengthens the decision process using the hybrid novel MCDM methodology. Additionally, this study differs from previous studies by presenting a comprehensive and novel hybrid methodology that comprehensively evaluates alternatives for solar

Table 2
Linguistic terms to evaluate alternative options.

Linguistic Term	(μ, ν)
AH-Absolutely High	(0.9, 0.05)
VH-Very High	(0.75, 0.2)
H-High	(0.65, 0.3)
M-Medium	(0.5, 0.45)
L-Low	(0.4, 0.5)
VL-Very Low	(0.3, 0.6)
AL-Absolutely Low	(0.15, 0.75)

panel waste recycling plant site selection according to multiple criteria. Including a wide range of criteria provides a detailed perspective on the inefficiencies in the decision-making process. IF-ITARA and IF-EDAS methods are robust MCDM approaches in decision-making processes (Kahraman et al., 2017; Liang, 2020; Mishra et al., 2020). The integration of IF-ITARA and IF-EDAS methods offers a robust and systematic approach to ranking alternative sites under fuzzy uncertainty, and it offers a stronger decision support mechanism. Moreover, this study provides a robust decision-making tool that effectively addresses uncertainties in the evaluation process and guides future studies.

3. Methodology

This paper proposes a two-level criteria hierarchy for selecting the optimal site for a solar panel waste recycling plant, drawing on both expert evaluations and comprehensive literature reviews. The main criteria and their corresponding sub-criteria are defined in the first phase. Subsequently, the IF-ITARA method is employed to calculate the criteria's weights systematically. IF-ITARA enables the detailed identification, classification, and prioritization of each criterion, ensuring their relative importance is rigorously evaluated and discussed. Following the weighting process, the alternative locations are ranked using the IF-EDAS method, which assesses each site's performance relative to the computed criteria weights. A comprehensive flowchart summarizing the entire methodology is presented in Fig. 1.

3.1. Preliminaries of intuitionistic fuzzy sets

IF Sets (IFSs) extend traditional Fuzzy Sets (FSs), which represent vagueness and fuzziness in human reasoning by assigning a membership degree to each element, expressed as a truth value between 0 and 1 (where 0 indicates complete falsity and 1 the complete truth) (Tumsekcali et al., 2021). Fuzzy logic was developed to focus on the problems with vague category features; however, FSs are limited in handling ambiguity and uncertainty because they consider only membership and implicitly assign the remaining part to non-membership.

To overcome these shortcomings, Atanassov introduced IFSs (Atanassov, 1986), which offer a more nuanced representation of uncertainty. Unlike traditional fuzzy sets, IFSs assign both a degree of membership (μ) and a degree of non-membership (ν) to each element, and importantly, the sum of these two values can be less than 1. The difference, known as the degree of hesitation or indeterminacy (π), explicitly quantifies the uncertainty or lack of knowledge about the membership status of the element.

This explicit treatment of hesitation is a key feature distinguishing intuitionistic fuzzy logic from traditional fuzzy logic, as it allows the model to directly account for situations where an expert is uncertain or indifferent. This capability provides enhanced flexibility and a more comprehensive depiction of ambiguity and hesitation in real-world decision-making problems (Ayyildiz et al., 2021; Liu, 2013)

Intuitionistic fuzzy numbers (IFNs) are mathematical constructs used to model uncertainty more effectively than standard fuzzy numbers. In an IFN, for any element x in a set X, the degree of membership $\mu(x)$, the degree of non-membership $\nu(x)$, and the degree of indeterminacy or hesitation $\pi(x)$ are all considered.

Definition 1. IFN $\widetilde{I}$ is given by.

$$\widetilde{I} \cong \{x, \widetilde{I}\,(\mu_{\widetilde{I}}(x), \nu_{\widetilde{I}}(x)); x \in X\} \tag{1}$$

where the functions $\mu_{\widetilde{I}}(x) : X \mapsto [0,1]$ and $\nu_{\widetilde{I}}(x) : X \mapsto [0,1]$ denote the membership and non-membership degrees of the element $x \in X$ to $\widetilde{A}$, with X being a fixed set. The degree of membership expresses how strongly x belongs to a set, while the non-membership expresses how

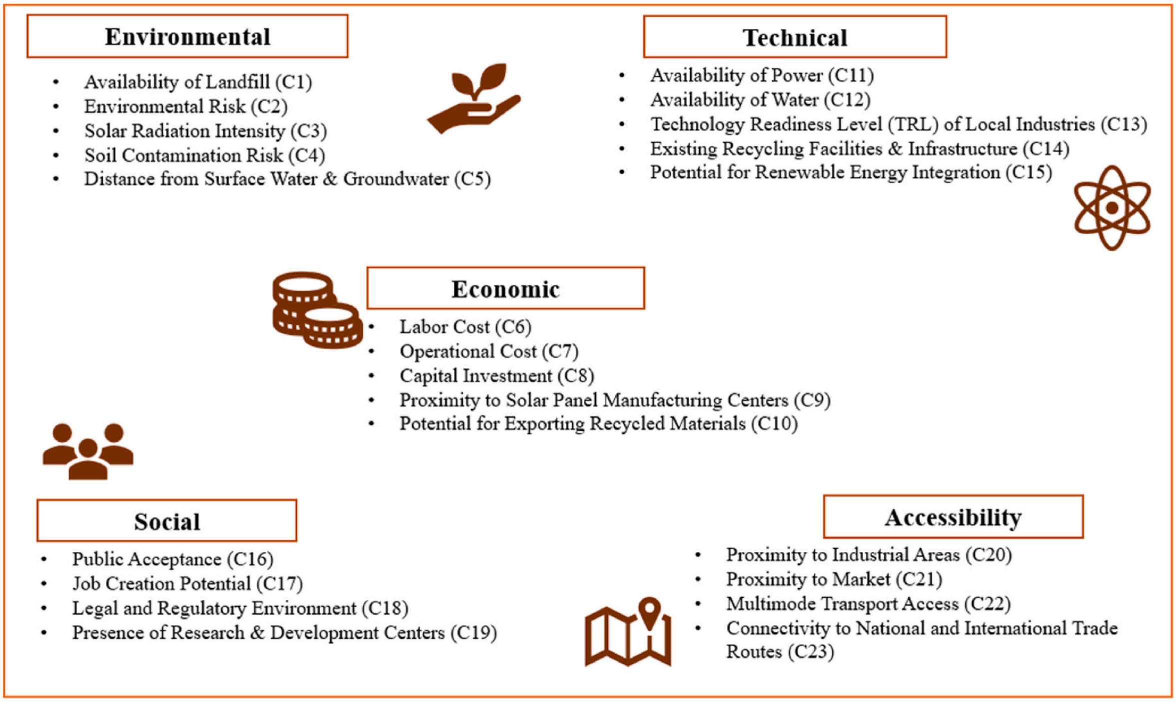

Fig. 2. Criteria set.

Table 3
Definitions of criteria.

Sub-criteria	Definitions	Ref.
Availability of Landfill (C1)	Having a landfill near the recycling facility reduces the environmental damage caused by transporting waste.	Sherif et al. (2022)
Environmental Risk (C2)	Environmental conditions must be suitable for the health of workers and the improvement of their work efficiency. The recycling facility must be in an area with good natural conditions to minimize the risk of affecting work efficiency.	(Sherif et al., 2022; Goh et al., 2024)
Solar Radiation Intensity (C3)	Measures the average level of solar energy received at a location, reflecting the potential scale of solar panel installations	Shorabeh et al. (2019)
Soil Contamination Risk (C4)	Assesses the likelihood and potential severity of soil contamination at a site.	Wang et al. (2024)
Distance from Surface Water & Groundwater (C5)	Recycling facilities should be away from Surface Water & Groundwater for public health and environmental protection.	Sherif et al. (2022)
Labor Cost (C6)	Labor cost in the region.	Shi et al. (2019)
Operational Cost (C7)	The total fixed and variable costs incurred during production, such as machine maintenance, energy, and machine depreciation.	Gomes et al. (2008)
Capital Investment (C8)	Includes land, construction, machinery procurement, labor skill development, disposal equipment, and vehicle acquisition costs.	Rafiquee et al. (2024)
Proximity to Solar Panel Manufacturing Centers (C9)	The proximity of recycling plants to solar panel manufacturing centers reduces logistics costs.	Expert view
Potential for Exporting Recycled Materials (C10)	Evaluates how effectively a location's infrastructure and connectivity enable the export of recycled materials.	Expert view
Availability of Power (C11)	Power is the basic requirement for the availability of these types of facilities.	Sherif et al. (2022)
Availability of Water (C12)	Water is the basic requirement for the availability of these types of facilities.	Sherif et al. (2022)
Technology Readiness Level of Local Industries (C13)	Measures the extent to which local industries are prepared and equipped with advanced technologies.	Expert view
Existing Recycling Facilities & Infrastructure (C14)	Assesses the availability, capacity, and condition of current recycling facilities and supporting infrastructure.	Expert view
Potential for Renewable Energy Integration (C15)	Gauges the suitability of a site for incorporating renewable energy sources into recycling operations.	Park et al. (2023)
Public Acceptance (C16)	The uninterrupted operation of the facility and its future development depend on public acceptance.	(Sherif et al., 2022; Shi et al., 2019)
Job Creation Potential (C17)	It focuses on employing people in nearby residential areas to boost local economic development.	Rafiquee et al. (2024)
Legal and Regulatory Environment (C18)	Assess how supportive or restrictive the local, regional, and national laws and policies are.	Expert view
Presence of Research & Development Centers (C19)	Economic advancement of the locality through job opportunities, infrastructure advancement activities and skill development through education for career development.	Sherif et al. (2022)
Proximity to Industrial Areas (C20)	Distance to industrial areas affects transportation costs.	Ayyildiz and Erdogan (2023)
Proximity to Market (C21)	Transportation costs are lower when waste recycling plants are close to markets.	Sherif et al. (2022)
Multimode Transport Access (C22)	Improves logistics flexibility, reducing expenses and enhancing market and resource availability.	Rafiquee et al. (2024)
Connectivity to National and International Trade Routes (C23)	Evaluate the degree of access a location has to major transportation networks, including highways, ports, and airports.	Kereush and Perovych (2017)

strongly it does not belong. The condition

$$0 \leq \mu_{\tilde{I}}(x) + \nu_{\tilde{I}}(x) \leq 1; x \in X \tag{2}$$

must hold, and the degree of hesitation is calculated as.

$$\pi_{\tilde{I}}(x) = \sqrt{1 - \mu_{\tilde{I}}(x) + \nu_{\tilde{I}}(x)} \tag{3}$$

The hesitation degree reflects the uncertainty or lack of knowledge about the membership status of x.

Let $\alpha = (\mu_{a}, \nu_{a})$ and $\beta = (\mu_{\beta}, \nu_{\beta})$ are two IFNs and λ is a positive scalar.

Definition 2. Some basic mathematical operations are given below (Xu and Yager, 2006). Basic mathematical operations for IFNs are defined to allow their combination and manipulation. These include addition ($\oplus$), multiplication ($\otimes$), scalar multiplication, and exponentiation, which are used to aggregate expert opinions and evaluate alternatives.

$$\alpha \oplus \beta = (\mu_{\alpha} + \mu_{\beta} - \mu_{\alpha}\mu_{\beta}, \nu_{\alpha}\nu_{\beta}) \tag{4}$$

$$\alpha \otimes \beta = (\mu_{\alpha}\mu_{\beta},\ \nu_{\alpha} + \nu_{\beta} - \nu_{\alpha}\nu_{\beta}) \tag{5}$$

$$\lambda\alpha = \left(1 - (1 - \mu_{\alpha})^{\lambda}, \nu_{\alpha}^{\lambda}\right), \lambda > 0 \tag{6}$$

$$\alpha^{\lambda} = \left(\mu_{\alpha}^{\lambda}, 1 - (1 - \nu_{\alpha})^{\lambda}\right), \lambda > 0 \tag{7}$$

Definition 3. The score function of α can be defined (Yan et al., 2010). The score function provides a way to rank or compare IFNs by computing a numerical value based on the membership and non-membership degrees.

$$S(\alpha) = \mu_{\alpha} + \mu_{\alpha}(1 - \mu_{\alpha} - \nu_{\alpha}) \tag{8}$$

Definition 4. Let $I_j = \left(\mu_j, \nu_j\right)$ be IFNs. The intuitionistic fuzzy weighted averaging (IFWA) operator (Liang, 2020). The IFWA operator aggregates several IFNs according to their weights, providing a combined assessment that accounts for both the magnitude and uncertainty in each expert's evaluation.

$$\text{IFWA}\ (I_1, I_2, \ldots, I_n) = \underset{j=1}{\oplus} w_j I_j = \left[1 - \prod_{j=1}^{n}\left(1 - \mu_j\right)^{w_j}, \prod_{j=1}^{n} \nu_j^{w_j}\right] \tag{9}$$

Where $w = (w_1, w_2, \ldots, w_n)^T$ is the weight vector of I_j.

3.2. IF-ITARA-EDAS framework

The ITARA method is a semi-objective weighting technique that leverages the theories of an indifference threshold (IT) and dispersion

Fig. 3. Alternative locations in Türkiye.

logic to form criterion importance level considering the available choices (Lin and Lo, 2023). Notably, ITARA is user-friendly and is stable than the entropy approach, particularly when dealing with a larger number of alternatives (Lo et al., 2021). ITARA was developed to address certain limitations observed in earlier MCDM methodologies. Unlike conventional methods that depend solely on pairwise comparisons or subjective judgments, ITARA introduces the notion of indifference thresholds. This feature allows it to capture the subtle preferences of decision-makers by explicitly accounting for the degree of indifference between criteria. Consequently, the weighting process becomes more robust and reflective of real-world decision-maker preferences.

The flexibility of ITARA is demonstrated by its successful application across a wide range of domains. Its capacity to manage diverse data types and integrate both objective data and subjective preferences in a structured, quantitative framework has proven valuable in many areas. For instance, in logistics and supply chain management, ITARA has been effectively used to select optimal equipment, such as warehouse stackers, by balancing conflicting criteria like cost, capacity, and operational efficiency (Ulutaş et al., 2020). In the field of waste management, the method has supported the selection and optimization of intelligent waste collection systems that must consider environmental, economic, and social sustainability dimensions (Hezam et al., 2024). Beyond these applications, ITARA has also shown significant promise in risk assessment and management. By reliably weighting factors such as severity, occurrence, and detectability, ITARA facilitates the ranking of alternatives based on overall risk profiles, a capability that is particularly valuable under conditions of uncertainty (Lo et al., 2021). Moreover, in sustainable development contexts, ITARA, especially when integrated with techniques like Z-number theory, has been instrumental in evaluating alternatives that span environmental, social, and economic considerations (Lin et al., 2024). Recent enhancements to the ITARA approach have involved incorporating fuzzy numbers, enabling the method to better handle the inherent ambiguity and vagueness in decision-making processes. The resulting IF-ITARA method is applied in this study for the first time to weight site selection criteria for solar panel waste recycling facilities. Although new to this application, IF-ITARA shows great promise as a robust approach for addressing complex decision-making problems across various domains.

The EDAS method identifies the optimal decision option by calculating the distance from the average solution (Ghorabaee et al., 2015). Unlike TOPSIS and VIKOR, which compare alternatives to ideal and anti-ideal solutions, EDAS assesses both the positive and negative distances from the mean to capture alternative desirability (Erdogan and Ayyildiz, 2022). EDAS is extended with IFNs to address evaluation fuzziness, forming the IF-EDAS approach.

To strengthen decision-making under uncertainty, this study introduces a novel hybrid methodology, the ITARA method, into the intuitionistic fuzzy environment for the first time, resulting in the development of the IF-ITARA. This extension allows for a more nuanced treatment of expert hesitation and uncertainty in criteria weighting, thereby contributing a new method to the literature. In parallel, the IF-EDAS method is integrated with the improved IF-ITARA framework to enable more robust ranking of alternatives under uncertainty. The combined use of IF-ITARA and IF-EDAS in this context represents a methodological novelty, as it offers an advanced, uncertainty-resilient tool for complex location selection problems where multiple stakeholders and imprecise judgments are involved. The following steps, adapted from (Kahraman et al., 2017; Liang, 2020; Mishra et al., 2020), outline the IF-ITARA-EDAS procedure.

Step 1. Construct a decision matrix where experts assess alternatives against criteria using the linguistic terms in Table 2.

Step 2. Aggregate expert evaluations into a single score using the IFWA operator.

$$\xi_{ij} = \left(\sqrt{1 - \prod_{e=1}^{l} \left(1 - \left(\mu_{ij}^{e}\right)^{2}\right)^{\Psi^{e}}}, \prod_{e=1}^{l} \nu_{ij}^{e\,\Psi^{e}} \right) \tag{10}$$

Where Ψ^e is the weight of expert e.

Step 3. Calculate the score value for the aggregated evaluations $S^*\left(\xi_{ij}\right)$.

Step 4. Normalize the decision matrix.

$$R_{ij} = \frac{S^*\left(\xi_{ij}\right)}{\sum_{l=1}^{m} \left(S^*\left(\xi_{lj}\right)\right)}, i = 1, \ldots, m; j = 1, \ldots, n \tag{11}$$

R_{ij} is the normalized evaluation of the alternative A_i under the criterion C_j.

Step 5. Equation (12) is used to rank the normalized evaluations of alternatives for each criterion in ascending order. This ranking process is fundamental for identifying the best and worst-performing

Table 4
Expert evaluations.

	E−1					E−2					E−3					E−4					E−5				
	A1	**A2**	**A3**	**A4**	**A5**	**A1**	**A2**	**A3**	**A4**	**A5**	**A1**	**A2**	**A3**	**A4**	**A5**	**A1**	**A2**	**A3**	**A4**	**A5**	**A1**	**A2**	**A3**	**A4**	**A5**
C1	M	M	M	M	M	VL	H	M	L	VH	VH	H	H	VH	M	M	AH	M	H	VH	H	VH	M	H	L
C2	H	VL	L	L	M	H	M	L	AH	VL	M	H	H	M	H	H	H	L	L	L	H	H	H	H	H
C3	AH	H	H	AH	VH	L	VH	M	H	AH	H	VH	M	VH	AH	M	VH	H	H	AH	AH	M	M	AH	VH
C4	L	L	L	L	M	L	H	M	VH	AH	M	M	M	M	M	M	M	M	M	M	VH	M	M	H	M
C5	VL	M	M	VL	H	VL	AH	H	L	VH	M	M	M	M	M	VH	L	H	VH	L	VH	VH	VH	VH	VH
C6	H	M	M	H	VL	L	VH	H	M	AH	VH	M	M	H	L	H	M	M	H	L	VH	L	L	VH	VL
C7	H	M	M	H	L	L	VH	H	M	AH	VH	M	M	H	L	H	M	M	H	L	H	M	M	H	L
C8	VH	H	VH	VH	L	VL	VH	H	L	AH	H	H	H	H	M	VH	H	H	VH	VL	VH	VH	H	VH	M
C9	L	M	M	L	M	AH	L	M	VH	VL	VH	H	H	H	M	AH	H	M	AH	L	VH	H	H	VH	L
C10	H	H	H	H	L	AH	L	M	VH	VL	H	M	M	H	L	VH	H	H	VH	M	H	M	M	H	L
C11	VH	VH	VH	VH	L	M	AH	VH	L	VL	VH	H	H	VH	M	AH	VH	H	AH	L	VH	H	H	VH	M
C12	AH	VH	VH	AH	M	VH	M	H	AH	L	H	H	H	H	M	VH	M	H	VH	M	VH	VH	VH	VH	H
C13	H	H	H	VH	M	AH	H	VH	M	L	VH	H	H	H	M	VH	H	M	AH	L	M	VH	VH	VH	L
C14	H	H	H	H	M	AH	H	VH	M	L	H	M	H	M	L	H	VH	H	VH	L	M	H	H	H	L
C15	VH	H	H	VH	M	VL	AH	M	L	VH	VH	H	H	H	M	VH	H	VH	H	L	VH	H	VH	VH	L
C16	VH	H	H	VH	M	L	AH	VH	M	H	H	M	M	H	M	H	H	H	H	L	VH	VH	VH	VH	L
C17	M	M	M	M	H	M	VH	H	L	AH	H	H	H	H	H	M	H	H	M	VH	VH	VH	VH	VH	M
C18	M	M	M	M	M	M	AH	VH	L	H	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L
C19	VH	H	M	H	L	AH	H	VH	M	L	VH	H	H	H	L	VH	H	H	H	L	VH	H	VH	VH	L
C20	VH	VH	AH	VH	L	AH	H	VH	M	L	VH	H	H	H	M	VH	VH	VH	AH	VL	VH	H	VH	VH	L
C21	VH	H	H	VH	L	AH	H	VH	M	L	VH	H	H	VH	M	VH	VH	VH	VH	VL	VH	H	H	VH	VL
C22	VH	M	M	VH	L	AH	H	VH	M	L	VH	H	H	VH	M	AH	H	H	AH	L	M	M	M	M	M
C23	VH	M	M	VH	M	VH	H	H	L	VL	VH	H	H	H	M	AH	M	M	AH	L	VH	M	VH	VH	VL

alternatives under each criterion, which is essential for the subsequent steps.

$$O_{(1)j} = \min_{1 \le i \le m} R_{ij} < \cdots < O_{(m)j} = \max_{1 \le i \le m} R_{ij}, j = 1, \ldots, n \tag{12}$$

$O_{(1)j}$ and $O_{(m)j}$ are the normalized evaluations under the core criterion C_j with the lowest (order one) and highest (order m), respectively.

Step 6. Determine the ordered distances.

$$\Lambda_{tj} = O_{(t+1)j} - O_{(t)j}, t = 1, \ldots, m-1; j = 1, \ldots, n \tag{13}$$

Λ_{tj} is the ordered distance between adjacent two normalized evaluations $O_{(t+1)j}$ and $O_{(t)j}$.

Step 7. Indifference threshold (IT_j) is determined by the expert team for each criterion, and then NIT_j values are determined.

$$NIT_j = \frac{IT_j}{\sum_{i=1}^{m} \xi_{ij}} \tag{14}$$

Step 8. Determine the significant ordered distances.

$$G_{tj} = \begin{cases} \Lambda_{tj} - NIT_j \middle| \Lambda_{tj} > NIT_j \\ 0 \middle| \Lambda_{tj} \le NIT_j \end{cases}, t = 1, \ldots, m-1; j = 1, \ldots, n; \xi > 0 \tag{15}$$

NIT_j represents the indifference threshold for core criteria; if Λ_{tj} exceeds NIT_j, then the corresponding ordered distance G_{tj} is considered significant and increases the importance of the core criterion C_j. Otherwise, it is deemed insignificant, and G_{tj} is set to zero.

Step 9. Calculate the importance.

$$\omega_j = \frac{\left(\sum_{t=1}^{m-1} G_{tj}^{\lambda}\right)^{1/\lambda}}{\sum_{l=1}^{n}\left(\sum_{t=1}^{m-1} G_{tl}^{\lambda}\right)^{1/\lambda}}, j = 1, \ldots, n; \lambda \in \{1, \ldots, \infty\} \tag{16}$$

Here, $\omega = (\omega_1, \ldots, \omega_j, \ldots, \omega_n)^T$ represents the vector of importance values assigned to the core criteria. The parameter λ is a distance measurement factor that reflects the preferred distance metric for computing the core importance. For example, setting $\lambda = 1$, $\lambda = 2$, and $\lambda = \infty$ corresponds to using the Manhattan distance, Euclidean distance, and Tchebycheff distance, respectively, when determining the core criteria importance.

Step 10. Compute the average solution for each criterion as follows.

$$A_j = [a_j]_{1 \times n} = \left(\sqrt{1 - \left(\prod_{k=1}^{m}\left(1 - \left(\mu_{i,j}\right)^2\right)\right)^{1/m}}, \prod_{k=1}^{m} \nu_{i,j}{}^{1/m}\right) \tag{17}$$

Step 11. Calculate the score value for the average solution $S^*(a_j)$.

Step 12. Equations (18) and (19) formulates the positive distance (PDA) and negative distance (NDA) matrices, which measure how much each alternative deviates from the average solution, separately for benefit (J^+) and cost (J^-) criteria. This calculation is crucial in the IF-EDAS methodology because it quantifies the relative performance of each alternative in a way that reflects both the direction (benefit or cost) and the degree of deviation.

$$PDA = [p_{ij}]_{l \times n} = \begin{cases} \dfrac{max(1, \exp(S^*(\xi_{ij}) - S^*(a_j)))}{\exp(S^*(a_j))} & if\ j \in J^+ \\ \dfrac{max(1, \exp(S^*(a_j) - S^*(\xi_{ij})))}{\exp(S^*(a_j))} & if\ j \in J^- \end{cases} \tag{18}$$

Table 5
Aggregated expert evaluations.

	A1		A2		A3		A4		A5	
	μ	v	μ	v	μ	v	μ	v	μ	v
C1	0.579	0.374	0.734	0.210	0.537	0.415	0.616	0.332	0.618	0.332
C2	0.626	0.325	0.578	0.374	0.526	0.408	0.659	0.279	0.531	0.414
C3	0.761	0.176	0.696	0.255	0.570	0.383	0.806	0.135	0.857	0.087
C4	0.544	0.399	0.521	0.424	0.483	0.460	0.588	0.360	0.656	0.290
C5	0.589	0.365	0.690	0.252	0.627	0.325	0.598	0.352	0.643	0.306
C6	0.666	0.283	0.558	0.391	0.521	0.424	0.651	0.300	0.596	0.339
C7	0.641	0.306	0.572	0.383	0.537	0.415	0.626	0.325	0.613	0.315
C8	0.682	0.270	0.695	0.255	0.674	0.277	0.688	0.261	0.628	0.314
C9	0.802	0.138	0.587	0.360	0.570	0.383	0.744	0.197	0.429	0.497
C10	0.750	0.193	0.556	0.391	0.570	0.383	0.695	0.255	0.407	0.508
C11	0.767	0.178	0.766	0.178	0.695	0.255	0.760	0.182	0.429	0.497
C12	0.780	0.164	0.653	0.300	0.695	0.255	0.818	0.125	0.521	0.424
C13	0.751	0.193	0.674	0.277	0.675	0.277	0.751	0.193	0.444	0.479
C14	0.716	0.227	0.651	0.300	0.674	0.277	0.627	0.325	0.423	0.490
C15	0.702	0.249	0.733	0.210	0.675	0.277	0.666	0.283	0.544	0.399
C16	0.666	0.283	0.734	0.210	0.675	0.277	0.675	0.277	0.505	0.433
C17	0.601	0.353	0.675	0.277	0.651	0.300	0.588	0.360	0.734	0.210
C18	0.483	0.460	0.646	0.296	0.558	0.391	0.464	0.469	0.505	0.433
C19	0.794	0.152	0.650	0.300	0.675	0.277	0.651	0.300	0.400	0.500
C20	0.794	0.152	0.695	0.255	0.780	0.164	0.751	0.193	0.407	0.508
C21	0.794	0.152	0.674	0.277	0.695	0.255	0.716	0.235	0.390	0.527
C22	0.807	0.135	0.599	0.353	0.627	0.325	0.735	0.210	0.444	0.479
C23	0.794	0.152	0.570	0.383	0.627	0.325	0.744	0.197	0.414	0.516

Table 6
Score values of aggregated evaluations.

	A1	A2	A3	A4	A5
C1	0.607	0.775	0.563	0.648	0.649
C2	0.656	0.606	0.561	0.700	0.560
C3	0.809	0.730	0.597	0.854	0.905
C4	0.575	0.550	0.510	0.619	0.691
C5	0.616	0.730	0.657	0.628	0.675
C6	0.700	0.587	0.550	0.683	0.635
C7	0.675	0.598	0.563	0.656	0.657
C8	0.714	0.730	0.707	0.723	0.665
C9	0.850	0.618	0.597	0.788	0.461
C10	0.793	0.586	0.597	0.730	0.442
C11	0.809	0.809	0.730	0.804	0.461
C12	0.823	0.684	0.730	0.865	0.550
C13	0.793	0.707	0.708	0.793	0.478
C14	0.757	0.683	0.707	0.657	0.460
C15	0.736	0.775	0.708	0.700	0.575
C16	0.700	0.775	0.708	0.708	0.536
C17	0.629	0.708	0.683	0.619	0.775
C18	0.510	0.683	0.587	0.495	0.536
C19	0.837	0.683	0.708	0.683	0.440
C20	0.837	0.730	0.823	0.793	0.442
C21	0.837	0.707	0.730	0.751	0.423
C22	0.854	0.628	0.657	0.776	0.478
C23	0.837	0.597	0.657	0.788	0.443

Table 7
Normalized decision matrix.

	A1	A2	A3	A4	A5	Aspire
C1	0.143	0.183	0.133	0.153	0.153	0.236
C2	0.161	0.148	0.137	0.171	0.137	0.245
C3	0.165	0.149	0.122	0.174	0.185	0.204
C4	0.146	0.139	0.129	0.157	0.175	0.253
C5	0.143	0.170	0.153	0.146	0.157	0.232
C6	0.169	0.141	0.132	0.164	0.153	0.241
C7	0.163	0.144	0.136	0.158	0.158	0.241
C8	0.157	0.161	0.156	0.159	0.146	0.220
C9	0.197	0.143	0.138	0.183	0.107	0.232
C10	0.191	0.141	0.144	0.176	0.107	0.241
C11	0.175	0.175	0.158	0.174	0.100	0.217
C12	0.177	0.147	0.157	0.186	0.118	0.215
C13	0.177	0.158	0.158	0.177	0.107	0.223
C14	0.177	0.160	0.166	0.154	0.108	0.235
C15	0.164	0.172	0.157	0.156	0.128	0.223
C16	0.158	0.175	0.160	0.160	0.121	0.226
C17	0.142	0.160	0.155	0.140	0.176	0.227
C18	0.134	0.179	0.154	0.130	0.141	0.262
C19	0.192	0.157	0.163	0.157	0.101	0.230
C20	0.181	0.158	0.178	0.171	0.095	0.216
C21	0.188	0.159	0.164	0.169	0.095	0.225
C22	0.194	0.143	0.150	0.177	0.109	0.228
C23	0.194	0.138	0.152	0.182	0.102	0.231

$$NDA = [n_{ij}]_{l\times n} = \begin{cases} \dfrac{max\left(1, \exp\left(S^*(a_j) - S^*(\xi_{ij})\right)\right)}{\exp\left(S^*(a_j)\right)} & if\ j \in J^+ \\ \dfrac{max\left(1, \exp\left(S^*(\xi_{ij}) - S^*(a_j)\right)\right)}{\exp\left(S^*(a_j)\right)} & if\ j \in J^- \end{cases} \tag{19}$$

Step 13–16. The remaining steps of the IF-EDAS methodology, including the calculation of weighted positive and negative distances, normalization, determination of appraisal scores, and final ranking of alternatives, are implemented following the standard procedures described in Kahraman et al. (2017). Readers may refer to this source for detailed mathematical formulations and algorithmic steps.

4. Case study: Türkiye

Türkiye, a rapidly developing country with a population of over 85

Table 8

Normalized evaluations ranked in ascending order.

	Rank1	Rank2	Rank3	Rank4	Rank5	Rank6
C1	0.133	0.143	0.153	0.153	0.183	0.236
C2	0.137	0.137	0.148	0.161	0.171	0.245
C3	0.122	0.149	0.165	0.174	0.185	0.204
C4	0.129	0.139	0.146	0.157	0.175	0.253
C5	0.143	0.146	0.153	0.157	0.170	0.232
C6	0.132	0.141	0.153	0.164	0.169	0.241
C7	0.136	0.144	0.158	0.158	0.163	0.241
C8	0.146	0.156	0.157	0.159	0.161	0.220
C9	0.107	0.138	0.143	0.183	0.197	0.232
C10	0.107	0.141	0.144	0.176	0.191	0.241
C11	0.100	0.158	0.174	0.175	0.175	0.217
C12	0.118	0.147	0.157	0.177	0.186	0.215
C13	0.107	0.158	0.158	0.177	0.177	0.223
C14	0.108	0.154	0.160	0.166	0.177	0.235
C15	0.128	0.156	0.157	0.164	0.172	0.223
C16	0.121	0.158	0.160	0.160	0.175	0.226
C17	0.140	0.142	0.155	0.160	0.176	0.227
C18	0.130	0.134	0.141	0.154	0.179	0.262
C19	0.101	0.157	0.157	0.163	0.192	0.230
C20	0.095	0.158	0.171	0.178	0.181	0.216
C21	0.095	0.159	0.164	0.169	0.188	0.225
C22	0.109	0.143	0.150	0.177	0.194	0.228
C23	0.102	0.138	0.152	0.182	0.194	0.231

Table 9

Differences between consecutive alternatives.

	R2-R1	R3-R2	R4-R3	R5-R4	R6-R5
C1	0.010	0.010	0.000	0.030	0.053
C2	0.000	0.011	0.012	0.011	0.074
C3	0.027	0.016	0.009	0.011	0.019
C4	0.010	0.006	0.011	0.018	0.078
C5	0.003	0.007	0.004	0.013	0.063
C6	0.009	0.012	0.012	0.004	0.072
C7	0.008	0.014	0.000	0.004	0.078
C8	0.009	0.002	0.002	0.001	0.060
C9	0.032	0.005	0.039	0.014	0.035
C10	0.035	0.003	0.032	0.015	0.050
C11	0.058	0.016	0.001	0.000	0.041
C12	0.029	0.010	0.020	0.009	0.029
C13	0.051	0.000	0.019	0.000	0.046
C14	0.046	0.006	0.006	0.012	0.057
C15	0.028	0.002	0.006	0.009	0.050
C16	0.037	0.002	0.000	0.015	0.051
C17	0.002	0.012	0.006	0.015	0.051
C18	0.004	0.007	0.013	0.025	0.083
C19	0.056	0.000	0.006	0.030	0.037
C20	0.062	0.014	0.007	0.003	0.035
C21	0.064	0.005	0.005	0.019	0.037
C22	0.034	0.007	0.027	0.018	0.033
C23	0.036	0.014	0.030	0.011	0.038

Table 10

Indifference threshold and sum of scores for each criterion.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
IT_j	0.1	0.1	0.1	0.15	0.2	0.2	0.2	0.2	0.1	0.15	0.1	0.1
Sum	3.241	3.083	3.895	2.945	3.307	3.154	3.149	3.539	3.313	3.146	3.612	3.652
NIT_j	0.031	0.032	0.026	0.051	0.060	0.063	0.064	0.057	0.030	0.048	0.028	0.027

	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
IT_j	0.1	0.1	0.15	0.1	0.1	0.1	0.15	0.2	0.2	0.1	0.1
Sum	3.478	3.264	3.494	3.427	3.413	2.812	3.350	3.625	3.447	3.392	3.321
NIT_j	0.029	0.031	0.043	0.029	0.029	0.036	0.045	0.055	0.058	0.029	0.030

Table 11

Discriminant results for criteria.

	R2-R1	R3-R2	R4-R3	R5-R4	R6-R5
C1	0	0	0	0	0.022
C2	0	0	0	0	0.041
C3	0.002	0	0	0	0
C4	0	0	0	0	0.027
C5	0	0	0	0	0.002
C6	0	0	0	0	0.009
C7	0	0	0	0	0.015
C8	0	0	0	0	0.003
C9	0.001	0	0.009	0	0.005
C10	0	0	0	0	0.002
C11	0.031	0	0	0	0.014
C12	0.001	0	0	0	0.002
C13	0.022	0	0	0	0.018
C14	0.016	0	0	0	0.026
C15	0	0	0	0	0.007
C16	0.008	0	0	0	0.022
C17	0	0	0	0	0.022
C18	0	0	0	0	0.048
C19	0.011	0	0	0	0
C20	0.007	0	0	0	0
C21	0.006	0	0	0	0
C22	0.005	0	0	0	0.004
C23	0.006	0	0.000	0	0.008

million, benefits significantly from solar energy, especially due to its favorable climate conditions. This situation necessitates solar panel waste recycling plants. As the country tries to develop its solar energy infrastructure, it is important to determine suitable locations for solar panel waste recycling plants. This study overcomes this challenge by focusing on strategically selecting locations for these plants in Türkiye. Selecting a suitable solar panel waste recycling plant location requires careful consideration of various factors, including environmental, economic and social impact. Fig. 2 comprehensively overviews the main and sub-criteria sets used in this case study to evaluate alternative locations.

The main and sub-criteria used for site selection of solar panel waste recycling facilities were systematically determined through a combination of expert opinions and an in-depth literature review. As illustrated

Table 12
Weights and ranks of the 23 sub-criteria considered for solar panel waste recycling site selection.

Sub-Criteria	Weight	Rank
Availability of Landfill (C1)	0.053	8
Environmental Risk (C2)	0.098	4
Solar Radiation Intensity (C3)	0.004	23
Soil Contamination Risk (C4)	0.065	7
Distance from Surface Water & Groundwater (C5)	0.005	22
Labor Cost (C6)	0.021	14
Operational Cost (C7)	0.035	11
Capital Investment (C8)	0.007	19
Proximity to Solar Panel Manufacturing Centers (C9)	0.036	10
Potential for Exporting Recycled Materials (C10)	0.006	21
Availability of Power (C11)	0.106	2
Availability of Water (C12)	0.007	20
Technology Readiness Level (TRL) of Local Industries (C13)	0.095	5
Existing Recycling Facilities & Infrastructure (C14)	0.100	3
Potential for Renewable Energy Integration (C15)	0.017	17
Public Acceptance (C16)	0.070	6
Job Creation Potential (C17)	0.052	9
Legal and Regulatory Environment (C18)	0.113	1
Presence of Research & Development Centers (C19)	0.026	13
Proximity to Industrial Areas (C20)	0.017	16
Proximity to Market (C21)	0.014	18
Multimode Transport Access (C22)	0.020	15
Connectivity to National and International Trade Routes (C23)	0.032	12

The results indicate that the Legal and Regulatory Environment (C18) is the most influential criterion, highlighting the importance of compliance with regulations and policies when selecting a solar panel waste recycling site. Availability of Power (C11) and Existing Recycling Facilities & Infrastructure (C14) are also highly weighted, emphasizing the necessity of a strong energy supply and established waste processing capabilities for efficient operations. On the other hand, Solar Radiation Intensity (C3) and Distance from Surface Water & Groundwater (C5) have the lowest weights, suggesting that while solar energy generation potential and water source proximity are relevant, they are not primary factors in site selection.

in Fig. 2, the criteria are structured under five main categories: Environmental, Technical, Economic, Social, and Accessibility.

In forming the criteria set, experts independently proposed potential criteria based on their domain knowledge and experience. All suggested criteria were then reviewed collectively. A criterion was included if there was a clear consensus among the majority of experts or if it was strongly supported by relevant literature. Criteria proposed by a single expert without literature support were further discussed within the expert panel, and only included if justified as essential for the study's context. The final set consists of 23 sub-criteria, with detailed definitions and corresponding references provided in Table 3.

Suitable alternative sites for solar panel waste recycling plants should be determined by considering numerous criteria in Table 3. At this step, five potential sites, Izmir (A1), Konya (A2), Kayseri (A3), Antalya (A4) and Sanliurfa (A5), are selected for the evaluation process. Türkiye is a country with high solar energy capacity, so this issue is particularly important for Türkiye; as the use of solar energy panels increases, the negative impacts on the environment will also increase. The country should also consider the waste recycling process of these panels. This study aims to contribute to the development of more sustainable and recyclable waste from solar panels in Türkiye by focusing on various regional characteristics and locations with solar energy potential. The locations of the identified alternatives in the country are given in Fig. 3.

For this study, expert evaluations were gathered from five academics specializing in various fields related to solar panel waste management and site selection. These experts were intentionally selected from the authors' professional academic network, ensuring that each panelist possessed substantial experience relevant to the study's focus. The experts were carefully selected to ensure a multidisciplinary perspective, allowing for a robust assessment. The panel includes researchers with expertise in renewable energy systems, industrial engineering, environmental sustainability, waste management, and energy policy. Some experts focus on solar energy technologies and the end-of-life management of photovoltaic systems; others specialize in waste management and environmental risk assessment. Additionally, an expert in supply chain logistics and industrial site planning provided valuable input on transportation efficiency and market accessibility. The diverse expertise within the panel ensures a comprehensive evaluation of both technical and socio-economic dimensions, leading to a well-informed and sustainable site selection process. All experts have demonstrated familiarity with Türkiye's local context and regulations, ensuring that the assessments are tailored to national conditions, though several also have international research experience, bringing a broader academic perspective. Each academic independently assessed the criteria based on domain knowledge, contributing to a balanced and objective decision-making framework. Expert opinions were obtained using a structured online questionnaire, allowing participants to provide their assessments remotely and independently, which ensured unbiased input and consistency in the evaluation process.

Step 1. A decision matrix is constructed for each expert by evaluating alternatives against criteria using the linguistic terms in Table 2. Table 4 presents the decision matrices for five experts.

Step 2. Expert opinions are converted to intuitionistic fuzzy numbers, and then the PFWA operator is used to aggregate expert evaluations. At this step, it is assumed that each expert has equal weight. Table 5 shows the aggregated expert evaluations.

Step 3. The score function is utilized to calculate the crisp values of aggregated evaluations. The score values of evaluations are shown in Table 6.

Step 4. The decision matrix is normalized. At this step, the highest score (aspiration level) for alternatives is 1. As an example, A1 has a score of 0.607 points under criterion C1, which is 0.393 points less than the aspiration level. The normalized decision matrix with aspiration level is given in Table 7.

Step 5. Normalized evaluations are ordered in ascending order to obtain Table 8.

Step 6. The differences between the scores of consecutive alternatives are calculated to generate Table 9.

Table 13
Average solutions for each criterion, showing membership, non-membership, and score values.

	μ	ν	Score		μ	ν	Score		μ	ν	Score		μ	ν	Score
C1	0.625	0.324	0.657	**C7**	0.600	0.346	0.632	**C13**	0.679	0.268	0.715	**C19**	0.661	0.285	0.697
C2	0.589	0.356	0.621	**C8**	0.674	0.274	0.709	**C14**	0.634	0.313	0.668	**C20**	0.717	0.229	0.756
C3	0.759	0.182	0.804	**C9**	0.660	0.285	0.696	**C15**	0.671	0.277	0.706	**C21**	0.683	0.266	0.718
C4	0.565	0.382	0.595	**C10**	0.620	0.327	0.653	**C16**	0.661	0.287	0.695	**C22**	0.671	0.274	0.708
C5	0.632	0.317	0.664	**C11**	0.709	0.236	0.748	**C17**	0.655	0.294	0.688	**C23**	0.662	0.286	0.696
C6	0.604	0.343	0.636	**C12**	0.715	0.231	0.753	**C18**	0.539	0.404	0.569				

Table 14
PDA and NDA values.

	PDA					NDA				
	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
C1	0.518	0.584	0.518	0.518	0.518	0.545	0.518	0.570	0.523	0.523
C2	0.537	0.546	0.571	0.537	0.571	0.557	0.537	0.537	0.581	0.537
C3	0.450	0.448	0.448	0.471	0.495	0.448	0.482	0.551	0.448	0.448
C4	0.563	0.577	0.600	0.552	0.552	0.552	0.552	0.552	0.565	0.608
C5	0.515	0.550	0.515	0.515	0.521	0.540	0.515	0.518	0.534	0.515
C6	0.530	0.556	0.577	0.530	0.530	0.565	0.530	0.530	0.555	0.530
C7	0.531	0.550	0.570	0.531	0.531	0.555	0.531	0.531	0.544	0.545
C8	0.492	0.492	0.493	0.492	0.515	0.495	0.503	0.492	0.499	0.492
C9	0.581	0.498	0.498	0.546	0.498	0.498	0.539	0.551	0.498	0.631
C10	0.598	0.520	0.520	0.562	0.520	0.520	0.557	0.551	0.520	0.643
C11	0.503	0.503	0.473	0.501	0.473	0.473	0.473	0.482	0.473	0.631
C12	0.505	0.471	0.471	0.526	0.471	0.471	0.505	0.482	0.471	0.577
C13	0.528	0.489	0.489	0.528	0.489	0.489	0.493	0.493	0.489	0.620
C14	0.561	0.521	0.534	0.513	0.513	0.513	0.513	0.513	0.518	0.631
C15	0.509	0.529	0.494	0.494	0.494	0.494	0.494	0.494	0.497	0.563
C16	0.502	0.541	0.505	0.505	0.499	0.499	0.499	0.499	0.499	0.585
C17	0.502	0.512	0.502	0.502	0.548	0.533	0.502	0.505	0.539	0.502
C18	0.566	0.634	0.576	0.566	0.566	0.600	0.566	0.566	0.610	0.585
C19	0.573	0.498	0.504	0.498	0.498	0.498	0.505	0.498	0.505	0.644
C20	0.509	0.470	0.502	0.487	0.470	0.470	0.482	0.470	0.470	0.643
C21	0.549	0.488	0.493	0.504	0.488	0.488	0.493	0.488	0.488	0.655
C22	0.570	0.493	0.493	0.528	0.493	0.493	0.534	0.518	0.493	0.620
C23	0.574	0.498	0.498	0.546	0.498	0.498	0.551	0.518	0.498	0.642

Table 15
Weighted and normalized distances of alternatives.

	A1. Izmir	A2. Konya	A3. Kayseri	A4. Antalya	A5. Sanliurfa
P_i^+	0.537	0.536	0.527	0.526	0.519
λ_i^+	1.000	0.998	0.980	0.978	0.967
N_i^-	0.524	0.519	0.521	0.527	0.591
λ_i^-	0.113	0.121	0.118	0.107	0.000

Step 7. Indifference threshold (IT_j) is determined by the expert team and then for each criterion and then NIT_j values are determined as shown in Table 10.

Step 8. The significant ordered distances are determined based on Eq. (15) and given in Table 11.

Step 9. Finally, the importance of the criteria is calculated and given in Table 12. All abbreviations and codes used in Table 12 are provided in the criteria definition section. Table 12 clearly presents the relative importance (weight) and rank of each sub-criterion, allowing for easy comparison of which factors are most influential in the decision process.

Step 10. Average solutions are calculated for each alternative as given in Table 13.
Step 11. The score values of average solutions are calculated as in Table 13, which presents the average membership, non-membership, and score values for each criterion calculated based on expert evaluations.

Step 12. The PDA and NDA values are determined according to the criterion type, as in Table 14. C2 (Environmental Risk), C4 (Soil Contamination Risk), C6 (Labor Cost), C7 (Operational Cost), and C8 (Capital Investment) are classified as cost-type criteria, where lower values are preferred. All remaining criteria are considered benefit-type, meaning higher values contribute positively to the site selection process.

Step 13. The weighted positive distance and weighted negative distance are calculated for each alternative.
Step 14. Distances are normalized as given in Table 15.

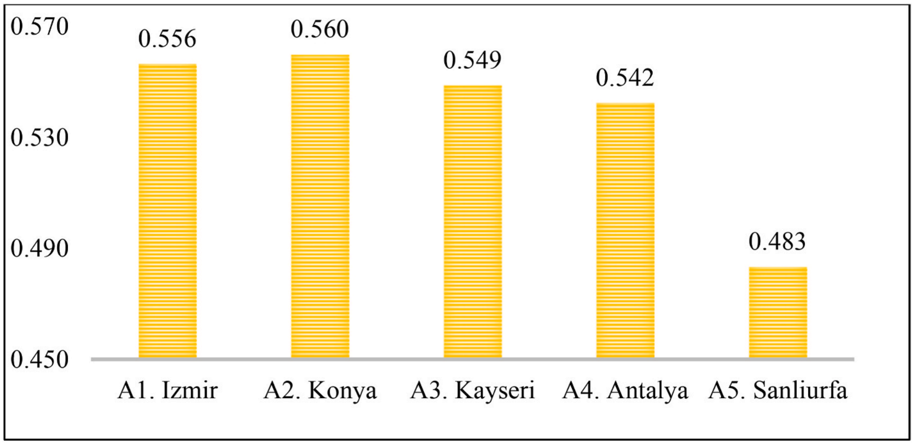

Fig. 4. Ranking of alternative locations.

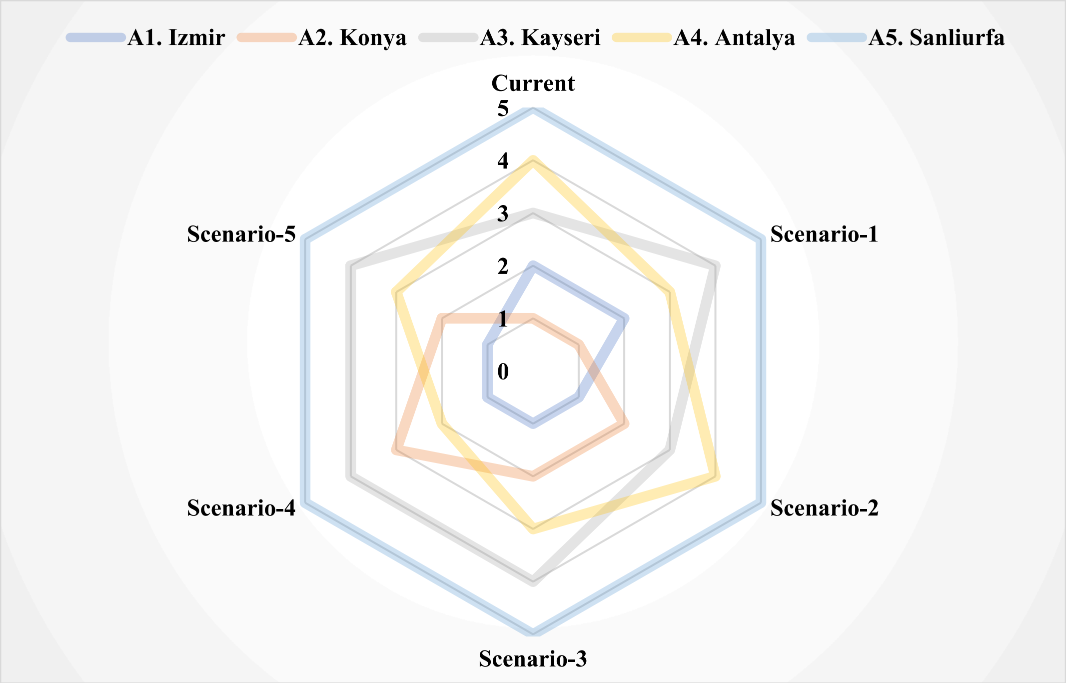

Fig. 5. Results of the sensitivity analysis.

Table 16
Expert weights for sensitivity analysis.

	E1	E2	E3	E4	E5
Current	0.2	0.2	0.2	0.2	0.2
S-1	0.5	0.125	0.125	0.125	0.125
S-2	0.125	0.5	0.125	0.125	0.125
S-3	0.125	0.125	0.5	0.125	0.125
S-4	0.125	0.125	0.125	0.5	0.125
S-5	0.125	0.125	0.125	0.125	0.5

The changes in alternative scores and rankings are then observed under these scenarios. For this purpose, the proposed methodology steps are reapplied, and the alternative scores are recalculated. Table 17 presents the alternative scores for the current and five sensitivity scenarios.

Table 17
Scores of alternatives for different scenarios.

	A1. Izmir	A2. Konya	A3. Kayseri	A4. Antalya	A5. Sanliurfa
Current	0.556	0.560	0.549	0.542	0.483
S-1	0.546	0.549	0.539	0.542	0.486
S-2	0.580	0.563	0.545	0.536	0.470
S-3	0.547	0.538	0.529	0.534	0.483
S-4	0.567	0.557	0.553	0.564	0.483
S-5	0.559	0.559	0.551	0.555	0.483

The results indicate that while the scores fluctuate slightly across different scenarios, the general trend remains consistent. The most significant deviation occurs in Scenario-2, where Izmir's score increases to 0.580, making it the highest-ranked location, whereas Sanliurfa's score decreases to 0.470, further reinforcing its position as the least favorable alternative. Similarly, Scenario-4 leads to a notable increase in Antalya's score (0.564), surpassing Kayseri and becoming the third-best alternative. The findings are visualized in Fig. 5, which illustrates the fluctuations in alternative rankings across different expert weighting scenarios.

Step 15. Finally, appraisal scores of alternatives are calculated.

Step 16. Alternatives are ranked based on their appraisal scores, as given in Fig. 4.

Fig. 4 presents the ranking of alternative locations for the solar panel waste recycling facility, highlighting Konya (0.560) and Izmir (0.556) as the most suitable options based on the evaluated criteria. These cities exhibit the highest scores, indicating their strong alignment with the key factors influencing site selection, such as infrastructure, regulatory support, and resource availability. Sanliurfa (0.483) ranks significantly lower than the other cities, indicating potential limitations such as weaker infrastructure, lower accessibility, or regulatory challenges that make it less favorable for establishing a recycling facility.

It should be noted that the proposed framework is not limited to the context of Türkiye. The model's structure and methodology are flexible, and both the criteria and expert inputs can be modified to suit the local conditions of any country or region. This makes the approach suitable for international applications in solar panel waste recycling site selection.

5. Sensitivity analysis

A sensitivity analysis is conducted to assess the impact of varying expert weight distributions on the ranking of alternative locations for the solar panel waste recycling facility. All experts are assigned equal weights (0.2 each) in the initial model. To evaluate the robustness of the results, five different scenarios are tested, where one expert is assigned a dominant weight of 0.5, while the remaining four experts share the remaining weight equally (0.125 each). Table 16 shows the expert weights for the sensitivity analysis.

In the baseline scenario, Konya ranks first, followed by Izmir, Kayseri, Antalya, and Sanliurfa. However, as expert weights shift, the rankings exhibit minor variations. Izmir ranks first in Scenarios 2, 3, 4, and 5, demonstrating its stability as a highly favorable location. Konya retains the top position in the baseline and Scenario-1 but falls to second place in most other cases. Sanliurfa consistently remains the lowest-ranked alternative across all scenarios, reinforcing its lower suitability for the recycling facility.

The sensitivity analysis confirms that the overall rankings are relatively stable, with Izmir and Konya consistently appearing as the top choices despite slight position changes depending on expert weighting adjustments. Sanliurfa remains the least preferred location across all tested scenarios. These results indicate that the decision-making model is robust and not highly sensitive to variations in expert influence, further validating the reliability of the ranking process.

While classical prediction error metrics (such as mean squared error or absolute error) are not directly applicable in fuzzy MCDM frameworks due to the analysis's qualitative and expert-driven nature, the proposed model's reliability was evaluated through sensitivity analysis. By systematically varying expert weights, the stability of the site rankings was assessed. The results indicate that the proposed approach provides robust decisions under different expert influence scenarios. Nevertheless, it should be noted that fuzzy MCDM methods inherently rely on subjective judgments, which may introduce uncertainties or variability in outcomes.

6. Results and discussion

This study provides scientific results for selecting a solar panel waste recycling plant. This study evaluated comprehensive criteria considering environmental, economic, and social effects. Thus, five main criteria and 23 sub-criteria are defined based on a literature review and five expert opinions. In the light of these criteria, five different locations were evaluated.

According to the results, the most important criterion in this decision process was the Legal and Regulatory Environment (C18) based on the social criterion. This criterion assesses how supportive or restrictive the local, regional, and national laws and policies are. Support from local organizations and the government is important for land acquisition and better sustainable performance for recycling facilities (Kumar et al., 2020). Additionally, social criteria, public opinion and acceptability play a vital role in the strategic construction, operation and sustainability of waste recycling facilities.

Availability of Power (C11) and Existing Recycling Facilities and Infrastructure (C14) are other important criteria with weight values of 0.106 and 0.100. A recycling facility needs basic facilities such as water, energy, etc. to operate effectively (Banar et al., 2014; Farahbakhsh and Forghani, 2019; Kharat et al., 2016; Queiruga et al., 2008). In general, hazarthe results show that technical and social criteria are considered more important for the solar panel waste recycling plant site selection process. In contrast, economic criteria and accessibility criteria were determined to be less important. However, according to Table 12, the weights are averaged based on the main criteria, the following ranking emerges: Technical = Social≻ Environmental≻ Economic= Accessibility. According to the results, governments and managers should now focus on social issues, technical requirements of recycling plants, and environmental protection through effective criteria in the site selection of solar panel waste recycling plants. Thus, sustainability is ensured. The findings at this stage provide an answer to how sustainability principles can be activated for plant location selection, which is actually the beginning of the solar panel waste recycling process. In this background, it offers significant criteria to be taken into consideration by the decision maker. The results show that accessibility and economic criteria are equally important among the criteria. However, in general, recycling is an intergenerational community good (Duggal et al., 1991). In this context, these sustainable approaches provide promising economic benefits to cities.

The most important environmental criterion was Environmental Risk (C2), with a weight value of 0.098. Although solar panels are environmentally friendly, they negatively affect the environment because they become hazardous waste after many years of use (Maghraby et al., 2025). In this case, environmental risks must also be taken into consideration. At the same time, environmental conditions must be suitable for both employee health and increased work efficiency. Among the criteria based on accessibility, the most important one was evaluated as Connectivity to National and International Trade Routes (C23). This criterion evaluates the degree of access a location has to major transportation networks, including highways, ports, and airports. In this way, the facility is both accessible and supports the reduction of logistics times and costs.

The alternative locations were ranked as A2 ≻ A1≻ A3≻ A4≻ A5 (see Fig. 4). Based on this ranking, the alternative location A2 (Konya) was selected as the best sustainable location for the solar panel waste recycling plant. This location has a large land area, is close to utilitarian resources such as water and energy, has low environmental risk and a high population density. In particular, A2, as seen in Table 4, was evaluated at least 'high' in the second most important criterion, Availability of Power (C11), and the fifth most important criterion, Technology Readiness Level (TRL) of Local Industries (C13). Similarly, four experts evaluated this alternative as 'high' and 'very high' by one for the third most important criterion, Existing Recycling Facilities & Infrastructure (C14). These situations support the selection of the alternative A2 as the most suitable location among the other alternatives. According to the results, A1 (Izmir) was ranked second among the other locations. This location is an alternative with a similarly high population density, is close to important resources such as water, fuel, etc., and has significantly better accessibility factors due to its location and level of development. Finally, location A5 (Sanliurfa) was selected as the last suitable alternative for this process due to many disadvantages such as proximity to the market, industrial area, etc., high investment costs, availability of water, power, the potential for renewable energy integration and technology readiness level of local industries. For example, according to Table 4, the experts evaluated this alternative location as the best degree of 'medium' in terms of Availability of Power (C11) and Local Industries (C13) criteria. Similarly, four experts evaluated this alternative as 'low' and 'medium' by one of the experts for the Existing Recycling Facilities & Infrastructure (C14) criterion. Such situations cause the A5 alternative to be selected as the least suitable location for solar panel waste recycling plants among the other alternatives. As can be seen, this study supports the hypotheses that the decision-making process for selecting suitable locations for solar panel waste recycling facilities can be improved and the criterion perspective can be expanded by using a fuzzy-based framework and addresses the evaluation phase of the alternatives together. Firstly, the criteria that are comprehensive and vital for this process from a sustainability perspective have been determined, and different alternative locations for Türkiye have been evaluated with a robust approach using a fuzzy-based hybrid novel methodology together with the opinions of the expert team in the field. The results guide decision makers in this important selection process and contribute to sustainable cities.

7. Conclusion

This paper emphasizes the critical importance of selecting solar panel waste recycling plants by identifying and ranking alternative locations tailored to Türkiye's unique background. For this purpose, it emphasizes that the location selection process of solar panel waste recycling plants is essential for more sustainable waste management with an approach supported by systematic and holistic assessment frameworks. Thanks to the innovative integration of IF-ITARA and IF-EDAS methods, it provides a robust framework to evaluate alternative locations according to a comprehensive set of criteria.

The findings emphasize that the most important criterion in the selection of the solar panel waste recycling plant site is the legal and regulatory environment. In addition, when the sub-criteria are considered, it has been determined that technical and social criteria are more important. This situation highlights that in selecting the location for these recycling plants, factors such as public acceptance, job creation potential, legal and regulatory environment, etc., should be evaluated by policymakers, managers, or governments, in addition to criteria such as availability of power and availability of water.

The results reveal that the proposed novel hybrid methodology effectively selects the most suitable location for solar panel waste recycling plants within sustainability goals. Consequently, the proposed approach offers actionable insights for governments, managers, and policymakers and sets a model for addressing uncertainty and complexity in decision-making processes. For example, depending on the results, environmentally focused management policies can be determined for both site selection and management of solar panel waste recycling plants. Perhaps government authorities can direct stakeholders in this decision process and play an active role in the evaluation processes. In addition, regulations could be considered to encourage solar panel manufacturers to take responsibility for reducing waste at the end of the life of these systems (Ngagoum Ndalloka et al., 2024). Moreover, the proposed methodology suggests a systematic approach that can be improved in different national contexts. Also, the results expose that Konya possesses the most suitable physical and environmental attributes and robust infrastructure, becoming the optimal site for solar panel waste recycling plant deployment. Additionally, this study contributes to the field of this process by providing a more detailed and comprehensive analysis that reflects the interrelation between environmental sustainability and effectiveness.

Although this study makes important contributions to the decision-making literature and the optimal site selection process for solar panel waste recycling plants, the limitations need to be acknowledged. For example, the assessment and weighting process, based solely on expert views, may lead to subjectivity and limit the objectivity of the results. The number and diversity of these experts were also limited, with only five experts participating in this study. It was hard to contain experts from broader fields, such as policy makers, managers, or urban planners, who have appropriate experience in determining and evaluating the criteria and alternatives. This expert team may affect the robustness and generalizability of the findings to diverse socio-economic or regional frameworks. Despite these limitations, a comprehensive and methodical hierarchy was effectively established and implemented, offering valuable perceptions for more sustainable and environmentally friendly cities. Future works can address these limitations by including a larger and more diverse expert team and stakeholders, and by validating the proposed context for different areas.

Further studies might extend the solar panel waste recycling plant site selection process by including factors like geopolitical stability or renewable energy integration. This would generate a more inclusive decision-making and evaluation framework. Additionally, the proposed methodology could be extended to another research area, such as renewable energy plants, thus broadening its pertinence. These aspects will further increase the applicability and robustness of the methodology, contributing to global efforts towards achieving green and sustainable transitions.

CRediT authorship contribution statement

Betul Yildirim: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Ertugrul Ayyildiz:** Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Nezir Aydin:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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