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Site Selection of Medical Waste Disposal Facilities Using the Interval-Valued Neutrosophic Fuzzy EDAS Method: The Case Study of Istanbul

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Abstract: In recent years, as a result of the increasing demand for health services, medical waste (MW) generated from health facilities has increased significantly. Problems that threaten the environment and public health may arise as a result of inadequate medical waste management (MWM), especially in densely populated metropolitan areas. Therefore, it is very important that the disposal process of waste is carried out in a way that minimizes harm to human health and the environment. MW disposal site selection is among the most important decisions that local governments make. These decisions have many conflicting and similar criteria and alternatives. However, decision-makers may experience significant uncertainty when evaluating the alternatives. This study adopts the interval-valued neutrosophic (IVN) fuzzy EDAS method for the evaluation of MW disposal facility siting alternatives in Istanbul. This approach is used to evaluate potential sites based on a comprehensive, hierarchical criteria framework designed to address data uncertainty and inconsistency common in multi-criteria decision-making (MCDM) scenarios. Within the scope of the study, six main criteria (distance settlement area, social acceptance, costs, environmental impacts, infrastructure facilities, and disaster and emergency) and nineteen sub-criteria are meticulously analyzed. Considering the geographical location and dense urban texture of Istanbul, the study emphasizes the criteria related to distance to residential areas, logistics costs, and potential disaster risks. Among the identified criteria, land costs, topographical features, proximity to landfills, and distance to high-voltage lines are emphasized as the least important criteria. This study, which evaluated various alternatives, identified Pendik, located on the Anatolian side of Istanbul, as the most suitable site for MW disposal due to its minimal risk. The study also compares the four main alternatives and highlights their relative strengths and weaknesses.

Keywords: medical waste; facility selection; multi-criteria decision-making; interval-valued neutrosophic fuzzy EDAS

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1. Introduction

In recent years, global population growth and increasing demands for healthcare services have led to a significant increase in the amount of medical waste (MW) generated in healthcare facilities. Especially after the coronavirus (COVID-19) pandemic, there has been a huge increase in MW, including sharp, infectious, pharmaceutical, pathological, and chemical waste [1]. MW, which contains a large number of bacteria, viruses, and chemicals, is one of the most important hazardous wastes according to the "National Hazardous Waste List" [2]. MW can be defined as: "waste resulting from the provision of health care services, including various materials such as used needles and syringes, body parts, blood, chemicals, medicines, medical devices and radioactive materials". Several classifications of MW have been proposed; the most widely accepted is that the main component of MW is the hazardous and non-hazardous fractions [3].

According to the World Health Organization (WHO) and the US Environmental Protection Agency, 10–25% of MW is reported to be hazardous MW and this percentage is increasing. The need for medical waste management (MWM) has increased during the COVID-19 period due to the increasing amount of MW and the fact that MW poses significant hazards to the environment and human health [4]. In addition, in low-income countries, although MWM is lower than in developed countries, it is increasing sharply due to increased access to health facilities. In more developed countries, the increase in MW is attributed to the aging population, which leads to an increase in the volume of healthcare waste [5]. Disposing of such a large volume of waste without threatening public and environmental health is crucial for public welfare.

Designing an effective system for transportation, collection, and disposal is very important for controlling diseases caused by these wastes. Hospitals, clinics, and other healthcare facilities, in particular, are generating more MW due to the increasing number of patients, various treatment methods, and medical supplies used. This increases the complexity and urgency of MWM. As a result of mismanaged MW, many viral diseases can spread to the environment and humans, threatening public health [6–8]. MW also promotes the growth and reproduction of insects, rodents, and vermin, causing water, air, and soil pollution, and unpleasant odors. It can also lead to immunodeficiency in humans and the transmission of diseases, such as cholera, hepatitis (B and C), and typhoid fever. Considering that the various types of MW can all cause different adverse effects, special attention should be paid to the management of MW in a way that does not put public and environmental health at risk. In this context, developing an integrated strategy for the management of MW is critical for healthcare organizations and communities. Strengthening regulations and guidelines at the local, national, and international levels can support the responsible management of MW and minimize environmental impacts.

Worldwide, MW is commonly disposed of using incineration and non-incineration technologies. Incineration technology refers to hot disposal technology and high-temperature thermal disposal technologies. Non-incineration technologies refer to low-temperature thermal treatment, chemical treatment technology, radiation treatment technology, biological treatment technologies, etc. [9]. Incineration-free technologies (steam and microwave sterilization) in MW disposal are suitable for infectious and pungent MW but not for pharmaceutical and chemical MW [10]. In addition, incineration technologies are suitable for almost all types of MW and can reduce its volume by approximately 85–90% (>800 °C). In Istanbul, approximately 90 tons of MW is collected and disposed of daily from over nine thousand health institutions. Of the collected MW, 15% is disposed of via incineration and 85% is disposed of using sterilization and solidification processes. There is one centralized incineration plant in Istanbul that provides MW incineration services. The existing waste incineration facility in Istanbul is the first and only facility of its kind in Turkey, operating at full capacity [11]. Therefore, a second centralized waste incineration plant is essential and should be able to meet the increasing demand. The planned waste incineration facility plays a significant role in the effective disposal of MW and the eradication of potentially harmful microorganisms [12]. These facilities oxidize waste at high temperatures, typically ranging from 850 to 1200 °C, thereby rendering harmful components inert [13]. Additionally, the potential of waste incineration facilities to generate energy contributes to the sustainability of waste management and enhances the more efficient utilization of natural resources [14].

Waste incineration is being rapidly developed, especially due to its advantages of energy recovery and volume minimization [15]. The improper management of incineration plants can lead to the release of carbon dioxide, heavy metals, and other pollutants during the disposal process and the generation of secondary pollution that damages the ecological environment. In short, it negatively affects the surface water, groundwater, air, and soil. Additionally, when selecting a site for an incineration facility, it is essential to comprehensively assess the distance to the settlement area, social acceptance, costs, environmental impacts, infrastructure facilities, disasters, and emergencies. Wrong decisions made during site selection without taking into account certain criteria can cause serious economic and environmental problems. In addition to economic damage, this process, which directly affects the environment and public health, should be meticulously handled with sustainable environmental criteria. The biggest task here belongs to expert decision-makers, and each criterion in site selection should be handled with care. This approach facilitates the identification of the most optimal site location. Therefore, the weighting of the criteria during the installation and operation of incineration plants is one of the important considerations in decision-making. As a result, the opinions of decision-makers are very important when environmental issues are considered.

Site selection is a complex spatial decision problem with a large variety of alternatives and different preferences for decision-makers. It is a critical decision, especially for a business or a project, and requires taking into account a number of factors. Thus, this choice is not easy and unilaterally definable [16]. The site selection of MW disposal facilities is a critical issue due to the huge impact of this waste on the ecology and environmental health of the region [17]. The selection of a new MW disposal facility is a complex process that requires considerable expertise in various social and environmental fields, such as soil science, engineering, hydrogeology, construction cost, earthquake, topography, land use, transportation, and economics [18]. In addition to the environmental and social requirements, the location to be selected must also meet health requirements and comply with local laws. In the literature, multi-criteria decision-making (MCDM) models have been successfully applied to many different site selection studies. MCDM is a tool that makes the optimal choice among different dependent criteria [19]. These methods offer a wide range of applications in urban and regional planning, land suitability mapping, and site selection. With the development of geographic information systems (GISs), various MCDM methods have found many applications. In the context of decision-making, a spatial MCDM/GIS approach can help decision-makers penetrate deeply into decision problems, rationally and systematically identify different levels of risk, and interpret phenomena.

In the literature, there are many types of studies on MW disposal, facility site selection, and MCDM methods. In a study where the analytical network process (ANP) and ELECTRE methods were applied to services covering incineration, microwave, on-site sterilization, off-site sterilization, and landfill activities in the disposal process of MW, it was determined that the "off-site sterilization" option would be the most ideal solution in both methods [17]. In another study [19], proposed a MCDM method based on gray theory for the problem of selecting cost-effective waste facilities that fulfill legal requirements and make the optimal choice in the presence of uncertainties. In a study on MW, a two-stage method was proposed to determine the facility areas that would serve in waste collection and disposal activities. In the first stage, suitable areas were identified with a GIS, and in the second stage, the ranking was made by taking into account the characteristics of the identified lands with the AHP, VIKOR, and PROMETHEE methods [20]. In two different studies conducted by two researchers working in the field of MCDM, the authors developed a new approach to be used in selecting cost-oriented suitable locations with the FAHP-GP model created by using the fuzzy analytical hierarchy process (FAHP) and goal programming (GP) in a hybrid way, taking into account the infrastructure, geological, social and environmental factors for the problem of identifying MW disposal facilities with an infectious risk. In another study [21], developed an approach to simultaneously determine the locations of MW disposal facilities, hospital locations, and the size of incinerators in facilities by using the Fuzzy AHP and Fuzzy Topsis methods in a hybrid manner.

According to another study on facility site selection, determining the location of MW disposal facilities is a growing problem for urban governments and health service providers. This problem becomes even more complex with legal regulations. In solving this problem, a practical and effective approach was developed in the decision-making process by using a hybrid of Fermatean fuzzy sets and WASPAS (weighted aggregated sum product assessment) methods [22]. Furthermore, in a similar study [23], developed the spherical fuzzy step-wise weight assessment ratio analysis (SFSWARA) approach by extending the spherical fuzzy sets (SFS) method to evaluate the uncertainties in the selection of MW landfills better, taking into account environmental, economic, and social criteria. In a GIS-based study, a GIS, the best-worst method (BWM), and the measurement of alternatives and ranking according to compromise-solution (MARCOS) methods were used in a hybrid way to determine the best alternatives for the facilities where the waste generated as a result of medical activities was to be stored [24]. In a post-COVID-19 study, a GIS-based approach that considered social, economic, and environmental criteria, together with objective and subjective data, was proposed to determine the location of facilities since the disposal of increasing amounts of MW would have a positive impact on preventing new possible health problems [25]. In a study on MW disposal processes, [26], used multi-criteria methods to select the most appropriate furnace to be used in the process of burning waste generated by healthcare services. Environmental, economic, social, and technical features were taken into consideration as the criteria. Two different methods were used together. The criteria weights were determined using the first method, the full consistency method (FUCOM), and the alternatives were ranked with the second method, the compromise ranking of alternatives from distance to ideal solution (CRADIS). In addition, a study with a high level of indecision, MCDM methods that can be used in uncertain situations that contradict each other and make the decision process difficult in the process of determining the locations of MW disposal facilities are proposed. A fuzzy PROMSIS method using TOPSIS and PROMETHEE was developed by considering five main criteria: economic, environmental, social, technical, and geological [27].

The aim of this study was to determine the best location for the establishment of a MW disposal facility in Istanbul. In the introductory part of the study, the best result was found by proposing a MCDM method, which is quite new in the literature and has not yet been applied to facility location problems. For this purpose, four different alternatives were determined as a result of the opinions received from experts in the Istanbul region. In order to eliminate the data uncertainty arising as a result of the criteria determined using the heuristic methods independently from these alternatives, it was preferred to form neutrosophic clusters. The fuzzy EDAS method used in the study guides decision-makers by using neutrosophic clusters and addresses incompleteness, uncertainty, and inconsistency in information. In the method section of the study, the fuzzy EDAS method was explained in detail, and then the criteria weights, clusters, and inconsistency ratios were determined in accordance with our problem. At the end of the study, all decision matrices were calculated, and the alternatives were ranked in order of importance among themselves.

2. Materials and Methodology

2.1. Study Area

Within the scope of this article, the city of Istanbul was determined as the study area. Istanbul is the most densely populated city among the 81 provinces of Turkey and is also one of the most important metropolises in the world. The study was conducted in the following area: latitude: 41.0122, longitude: 28.976, located between the coordinates 41°0′44″ north, 28°58′34″ east. Istanbul has a surface area of 5343.00 km^2. Istanbul, which connects the continents of Asia and Europe, is also located in the strait connecting the Black Sea and the Marmara Sea. Thanks to this important location, it has been one of the most important centers in the world in transportation and trade activities throughout history.

The city has the advantage of its geopolitical location, which has led to the establishment of the headquarters of important industrial and financial institutions in Turkey. All modes of transportation are available in the city to support industrial and commercial activities. There are two international airports in the city. There are railway facilities, such as light rail transportation, suburban lines, and high-speed trains. As an alternative to Turkey's ports located in the Gulf of Izmit, in addition to the ports located in the west of Istanbul, there is the Haydarpasa port located on the Bosphorus and connected by rail. The Bosphorus within the city connects Europe and Asia with suspension bridges at three different locations.

In terms of educational opportunities, Istanbul is also one of the centers of education in the region, with 57 universities, including 13 public and 44 foundation universities, including internationally recognized universities.

Used as the capital by different civilizations throughout history, Istanbul has a rich historical and cultural structure. Thanks to this feature, the city constantly attracts the attention of local and foreign tourists and hosts millions of tourists every year.

Istanbul, which currently has approximately 18.5% of Turkey's population, is becoming more densely populated as a result of economic, educational, and cultural activities. The city needs to improve its service quality in a sustainable structure by further developing its existing attraction opportunities. Focusing on this purpose, it is important to collect and dispose of MW with scientific approaches to support the city to have more livable, healthy, and environmentally friendly facilities.

For a more detailed understanding of the study area, three maps were created in stages (Figure 1).

Map 1 indicates which region of Turkey the study covers.

Map 2 shows the general borders of Istanbul, which is located in the Marmara region of Turkey and is the most densely populated city in terms of population. It also shows four districts in Istanbul and the locations of the facilities to be located between these boundaries.

Map 3 shows the data details used within the scope of the study. The data of 1,460,280 building areas and 2057 health units located throughout Istanbul were taken into consideration.

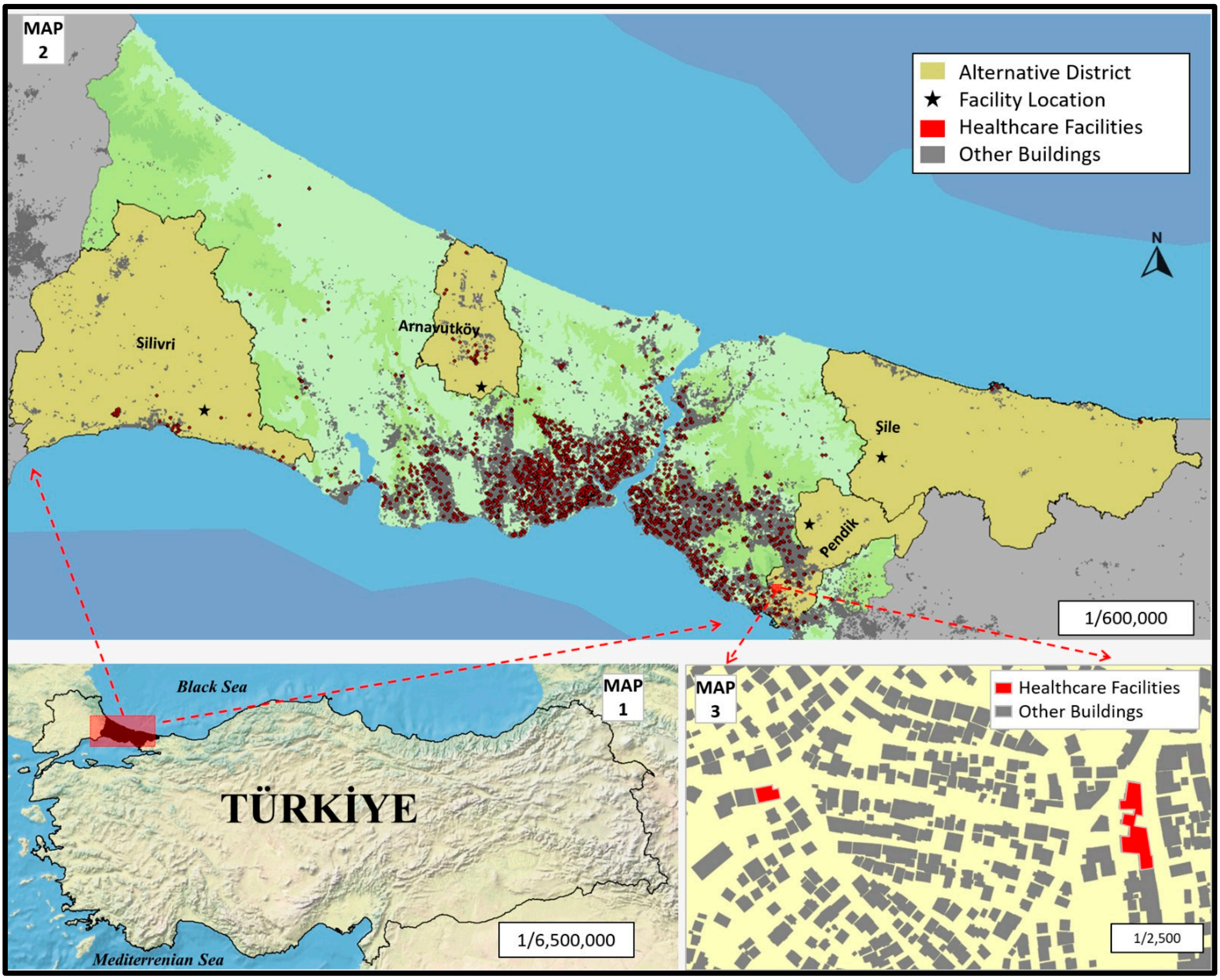

Figure 1. Geographic location of the study area.

2.2. Methodology

2.2.1. Interval-Valued Neutrosophic Fuzzy EDAS

The evaluation based on distance from average solution (EDAS) method is commonly used in multi-criteria group decision-making (MCGDM) to handle conflicting criteria. This method, pioneered by [28], effectively identifies conflicting attributes via calculating the average solution using the positive distance from average (PDA) and negative distance from average (NDA). Subsequent research by [29–31], has expanded the applications of the approach. They introduced a neutrosophic soft decision approach, incorporated hesitant fuzzy information, and explored hybrid operators.

The EDAS method was extended to the interval-valued fuzzy environment and used in site selection with interval fuzzy information by [32]. It was also applied to group decision-amaking with interval fuzzy information [33]. Also [34] further improved the EDAS method by integrating interval-valued neutrosophic (IVN) information, which enhances its adaptability to different decision-making scenarios. In addition [35], implemented an energy-saving design for a green building in an intuitionistic fuzzy environment with a group decision-making process.

Ref. [36] used neutrosophic sets to account for decision-makers' (DM) opinions and tendencies, and to detect the DM T (truthiness), F (falsity), and I (indeterminacy).

Definition 1. *The set of IVN is indicated by using the following:*
$x_j = \langle [T^L_j, T^U_j], [I^L_j, I^U_j], [F^L_j, F^U_j] \rangle$, where j pertains to the deciders (j = 1,2,3, …. n).
The INWAA operator, which is based on the weighted aggregation operators of the IVNNs, can be calculated using Equation (1):

$$(x1, x2. \dots . xn) = \sum_{k=1}^{n} y_k \, x_j \quad (1)$$

The formula represents a set of three intervals, each containing a product of n terms. The terms are calculated using the variables TL, TU, IL, IU, FL, and FU, and the weight assigned to the decision-maker, y_k, which indicates its level of importance.

Definition 2. *Equation (2) determines the ranking operation of IVNN as follows:*

$$K(x)=\frac{\left(T_x^L*(2-I_x^L-I_x^U)\right)+\left(T_x^U*(2-I_x^L-I_x^U)\right)+(1-F_x^L)*(2-I_x^L-I_x^U)+(1-F_x^U)*(2-I_x^L-I_x^U)}{8} \quad (2)$$

where $x = \langle [T^L_x, T^U_x], [I^L_x, I^U_x], [F^L_x, F^U_x] \rangle$

Definition 3. *To determine the highest value within the range of zero and IVN, apply Equation (3).*

$$Z(x_j) = \begin{cases} x_j, & if \;\; K(x_j) > 0 \\ 0, & if \;\; K(x_j) \le 0 \end{cases} \quad (3)$$

where $x = \langle [T^L_j, T^U_j], [I^L_j, I^U_j], [F^L_j, F^U_j] \rangle$ *and* $0 = \langle [0,0], [1,1], [1,1] \rangle$

Definition 4. *In X, an IVN set N can be defined using three membership functions: a truth membership function* $T_N(x)$*, an indeterminacy membership function* $I_N(x)$*, and a falsity membership function* $I_N(x)$*, each corresponding to* $x \in X$*.*

$$T_N = \left[T^L_{N(x)}, T^U_{N(x)} \subseteq [0,1]\right], I_N(x) = \left[I^L_{N(x)}, I^U_{N(x)} \subseteq [0.1]\right] \text{ ve } F_N(x) = \left[F^L_{N(x)}, F^U_{N(x)} \subseteq [0,1]\right]$$

This IVN set must meet the condition of $0 \le T^L_{N(x)} + I^L_{N(X)} + F^L_{N(x)} \le 3$
The IVNS can be expressed as follows:

$$N = \left\{\langle x. \left[T^L_{N(x)}, T^U_{N(x)}\right], \left[I^L_{N(x)}, I^U_{N(x)}\right], \left[F^L_{N(x)}, F^U_{N(x)}\right] \rangle \mid x \in X\right\} \quad (4)$$

Although IVNS can be expressed as Equation (4), The IVNS is denoted as $[T^L_N, T^U_N], [I^L_N, I^U_N], [F^L_N, F^U_N]$ *to reduce the complexity.*
Let $[T^L_a, T^U_a], [I^L_a, I^U_a], [F^L_a, F^U_a]$ *and* $b = [T^L_b, T^U_b], [I^L_b, I^U_b], [F^L_b, F^U_b]$ *be two NNs.*
The relationships between them are illustrated below:

1. $a^c = \langle [T^L_a, T^U_a], [1 - I^L_a, 1 - I^U_a], [F^L_a, F^U_a] \rangle$;
2. $a \subseteq b$ *if and only if* $a \subseteq b$ *and only if* $T^L_a \le T^L_b, T^U_a \le T^U_b; I^L_a \ge I^L_b, I^U_a \ge I^U_b; F^L_a \ge F^L_b, F^U_a \ge F^U_b$ *a* = *b if and only if a* ⊆ *b and b* ⊆ *a*;
3. $a \oplus b = \langle [T^L_a + T^L_b - T^L_a T^L_b, T^U_a + T^U_b - T^U_a T^U_b], [I^L_a I^L_b, I^U_a I^U_b], [F^L_a F^L_b, F^U_a F^U_b] \rangle$;
4. $a \otimes b = \langle [T^L_a T^L_b, T^U_a T^U_b], [I^L_a + I^L_b - I^L_a I^L_b, I^U_a + I^U_b - I^U_a I^U_b], [F^L_a + F^L_b - F^L_a F^L_b, F^U_a + F^U_b - F^U_a F^U_b] \rangle$.

Definition 5. *Equation (5) is used to calculate the IVN set subtraction.*

$$x \ominus y = \langle \left[T_x^L - T_y^U, T_x^U - T_y^L\right], \left[\mathrm{Max}\left(I_x^L . I_y^L\right), \mathrm{Max}\left(I_x^U . I_y^U\right)\right], \left[F_x^L . F_y^U, F_x^U - F_y^L\right] \rangle \quad (5)$$

where $x = \langle [T_x^L, T_x^U], [I_x^L, I_x^U], [F_x^L, F_x^U] \rangle$ ve $y = \langle [T_y^L, T_y^U], [I_y^L, I_y^U], [F_y^L, F_y^U] \rangle$

Definition 6. *Considering an INV number* $A = \langle [T^L . T^U] . [I^L . I^U] . [F^L . F^U] \rangle$ *the deneutrosophicated value* (x) *is calculated using Equation (6):*

$$K(A) = \frac{T^L + T^U + 2 - F^L - F^U + T^L * T^U + \sqrt{(1-F^L)*(1-F^U)}}{6} * \left[\left(1 - \frac{I^L + I^U}{2}\right) - (\sqrt{I^L * I^U}\right] \quad (6)$$

2.2.2. Steps of the Interval-Valued Neutrosophic EDAS Method

The first step of the IVN-EDAS method involves creating a linguistic decision matrix for the criteria and alternatives using nine specific linguistic terms derived from expert input. All three experts consulted in the study have considerable experience in this field and have previously been involved in projects to establish MW disposal facilities. Expert 1 has slightly more experience than the other two experts. Expert 1 has also been involved in MW disposal facility projects abroad. For this reason, the evaluation weights of the experts were taken as 0.40, 0.30, and 0.30, respectively.

These decision matrices consisting of linguistic expressions were converted into the neutrosophic format. Then, they were merged and the weighted matrices were obtained. The numerical operations in this study used neutrosophic definition formulas. Finally, the alternatives were ranked based on the final evaluation score. Figure 2 shows the steps in the IVN-EDAS method.

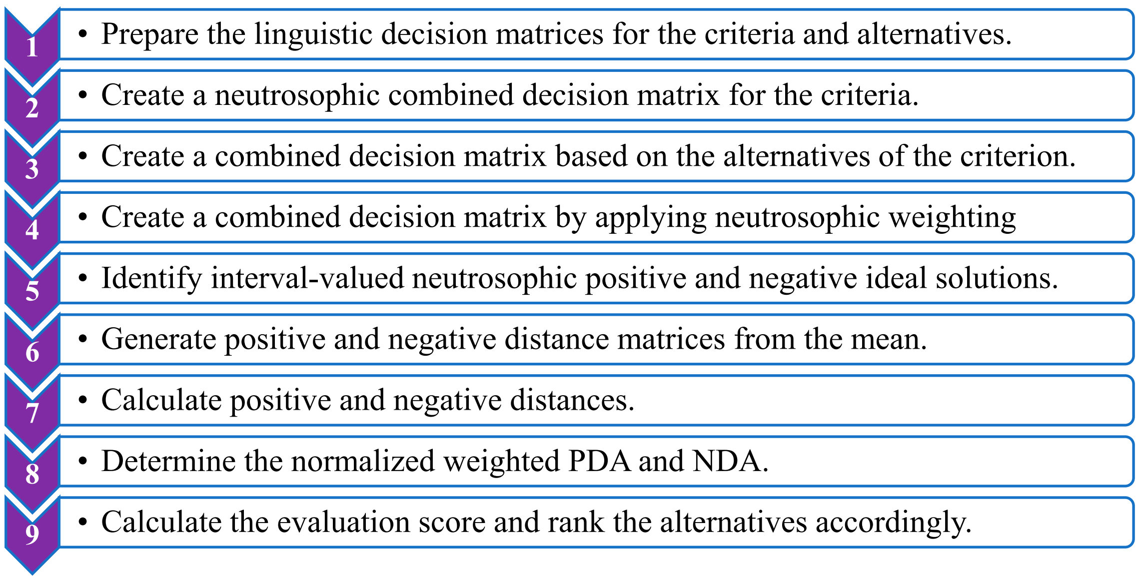

Figure 2. IVN-EDAS process steps.

The IVN decision matrix Dj was created using expert opinions (j) to evaluate the benefit (b_{mn}) and cost (c_{mn}) variables. The alternatives (n) are listed in the columns and the criteria (m) are listed in the rows. A scale with linguistic phrases and values was used (refer to Table 1). Finally, the IVN decision matrix (Dj) with linguistic terms was converted into IVN numbers.

Table 1. IVN decision matrix scales and linguistic terms.

	Linguistic Terms	⟨T, I, F⟩
CL	Certainly Low	⟨[0.15, 0.25], [0.15, 0.25], [0.85, 0.95]⟩
VL	Very Low	⟨[0.25, 0.35],[0.35, 0.45], [0.75, 0.85]⟩
L	Low	⟨[0.35, 0.45], [0.45, 0.55], [0.65, 0.75]⟩
BA	Below Average	⟨[0.45, 0.55], [0.55, 0.65], [0.55, 0.65]⟩
A	Average	⟨[0.55, 0.60], [0.65, 0.75], [0.45, 0.55]⟩
AA	Above Average	⟨[0.55, 0.65], [0.55, 0.65], [0.45, 0.55]⟩
H	High	⟨[0.65, 0.75], [0.45, 0.55], [0.35, 0.45]⟩
VH	Very High	⟨[0.75, 0.85], [0.25, 0.35], [0.25, 0.35]⟩
CH	Certainly High	⟨[0.85, 0.95], [0.15, 0.25], [0.15, 0.25]⟩

After combining the decision matrices with the IVN decision matrix and calculating the mean, the experts produced the mean solution matrix ($W = [wj]_{1m}$) for the criterion weights using Equation (1). Decision-makers assigned linguistic weights to the criteria by converting the linguistic expressions into IVN numbers, as shown in Table 2.

Table 2. IVN decision matrix (aggregated).

Criterion	Type	AL1	AL2	…	ALN
C11	Linguistic Cost	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$	…	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$
C12	Numerical Cost	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$	…	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$
⋮	⋮	⋮	⋮	⋮	⋮
Cm	Linguistic Benefit	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$	…	$\langle[T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle$

The AV_n matrix of the average criterion weights was calculated by adding up all the IVN criterion weights using the IVN-weighted arithmetic mean. To represent the performance values for the nth alternative's positive and negative distance from the mean solution in terms of the mth criterion, we used the formulas for positive deviation analysis (PDA) and negative deviation analysis (NDA) (Equations (7) and (8)). The selection of the equations depended on the orientation of the criterion, whether it was benefit-oriented or cost-oriented.

$$pda_{mn} = \begin{cases} \frac{Z(x_{mn} \ominus AVn)}{K(av_n)}, \text{if } m \in \text{B ise} \\ \frac{Z(AV_n \ominus X_{mn})}{K(av_n)}, if\ m \in C\ ise \end{cases} \tag{7}$$

$$nda_{mn} = \begin{cases} \frac{Z(AV_n \ominus X_{mn})}{K(av_n)}, \text{if } m \in \text{B ise} \\ \frac{Z(x_{mn} \ominus AVn)}{K(av_n)}, \text{if } m \in C\ ise \end{cases} \tag{8}$$

Equation (9) displays the sp_n and np_n formulas. The normalized values for sp_n and np_n were computed for all the alternatives using Equations (10) and (11) after normalizing the values.

$$sp_n = \sum_{n=1}^{l}(w_j \otimes pda_{mn}) \qquad np_n = \sum_{n=1}^{l}(w_j \otimes nda_{mn}) \tag{9}$$

$$nsp_n = \frac{sp_n}{max\,(K(sp_n))} \tag{10}$$

$$nsn_n = 1 - \frac{sn_n}{max\,(K(sp_n))} \tag{11}$$

The evaluation score was calculated using Equation (12), taking into account all the alternatives. The scores were then ranked in descending order.

$$as_n = \frac{1}{2}(nsp_n \oplus nsn_n) \tag{12}$$

3. Case Study and Results

In our study, we analyzed six dimensions to determine the criteria for selecting a location for a MW disposal facility. After conducting a literature review, we defined 19 criteria and four alternative locations based on the dimensions of “distance to settlement Area”, “social acceptance”, “costs”, “environmental impacts”, “infrastructure facilities”, and “disaster and emergency”, as shown in Figure 3. Subsequently, we collected evaluations from three experts through face-to-face interviews.

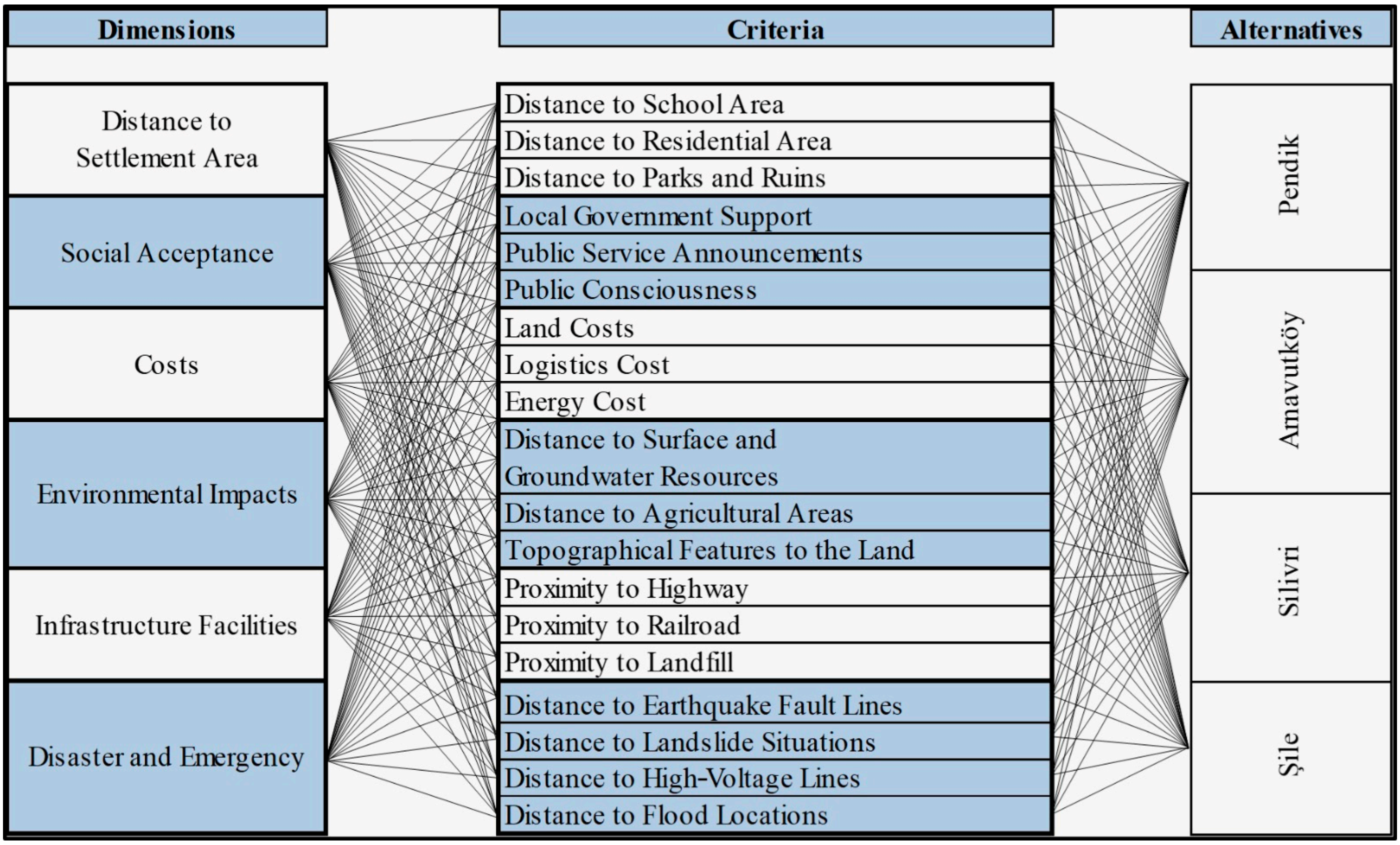

Figure 3. Dimensions, criteria, and alternatives for the site selection decision problem.

The IVN fuzzy EDAS method facilitated the ranking and prioritization of the alternatives, incorporating neurotrophic fuzzy EDAS for the sub-criteria and weights. Decision-makers used the IVN matrices, adhered to the criteria standards, and assigned linguistic terms to the alternatives. Although some of the criteria in the study were cost-based and some were benefit-based, to facilitate the process during the expert interviews, questions were asked and scored so that all criteria were benefit-based. For example, the cost of land was a cost-based criterion. However, when comparing the alternatives in the study, we stated that we would consider the cost of land as a preferred benefit. We asked for a benefit-based evaluation by asking which alternative was more preferable or advantageous according to the land costs criterion. As this approach was taken for all the criteria, all the criteria were considered to be benefit-based in the calculations. Table 3 summarizes the initial findings of the three experts using nine linguistic terms to express the differences in impact.

In Figure 3, the alternatives are listed in order as Pendik, Arnavutköy, Silivri, and Şile. In addition, Table 3 shows the explanations of the identified criteria and similar articles using these criteria.

Table 3. Explanations of the criteria.

ID	Criteria	Explanation of the Criteria	Covered by
C1.1	Distance to School Area	It is critical to reduce the risk of exposing students to harmful emissions and protect the air quality.	This article
C1.2	Distance to Residential Area	It plays a critical role in maintaining air quality and protecting overall public health.	[37]
C1.3	Distance to Parks and Ruins	It ensures that recreational areas remain clean and safe, while minimizing respiratory and general health risks to the public.	[38]
C2.1	Local Government Support	It has a critical role in establishing the necessary infrastructural and regulatory framework to ensure the efficient and orderly operation of the facility.	[39]
C2.2	Public Service Announcements	It aims to build a mutual understanding and support through transparent information-sharing about the environmental and health impacts of the facility and by addressing community concerns.	This Article
C2.3	Public Consciousness	Public awareness of waste management increases community involvement and encourages a more informed attitude in assessing environmental and health impacts.	This Article
C3.1	Land Costs	The cost of land is often a large part of the project budget and plays a decisive role in the overall profitability of the investment, as well as the local economy and environmental impacts.	[40]
C3.2	Logistics Cost	The fast and safe transportation of MW to disposal facilities is an important criterion, and the proximity of the facility to hospitals reduces waste transportation costs.	[40]
C3.3	Energy Cost	As it constitutes a significant portion of the operating budget, it is very important in terms of sustainable operational efficiency.	[41]
C4.1	Distance to Surface and Groundwater Resources	It is of great importance for environmental risk management and public health, as the possibility of leaking waste from these facilities entering groundwater can lead to the contamination of water resources and thus widespread ecological and health problems.	[42]
C4.2	Distance to Agricultural Areas	Potential contaminants and air pollution emitted from these facilities jeopardize the safety and quality of agricultural products, threatening consumer health.	[43]
C4.3	Topographical Features to the Land	In particular, it affects the facility's core functions such as waste management and water drainage. Sloping and irregular terrain can increase the risk of flooding and erosion, jeopardizing both the structural integrity of the facility and the protection of surrounding ecosystems.	[43]
C5.1	Proximity to Highway	Logistics is critical for efficiency and emergency responses because the accessibility of facilities directly affects the safe and efficient transportation of waste.	[43]
C5.2	Proximity to Railroad	Railroad access provides a significant logistical advantage, especially when transporting large volumes or hazardous waste. The strategic planning of the distance helps to reduce the operational costs of the facility.	[44]

C5.3	Proximity to Landfill	It can help minimize environmental impacts and maintain effective waste management by facilitating the rapid and safe transportation of ash and slag from waste incineration to landfills.	[37]
C6.1	Distance to Earthquake Fault Lines	Facilities located close to earthquake fault lines are at risk of severe damage during seismic activity, which can compromise the integrity of the facility and lead to leakage of hazardous waste into the environment.	This article
C6.2	Distance to Landslide Situations	Facilities located in areas with a high risk of landslides can be severely damaged by natural disasters, which can cause hazardous waste inside the facility to leak into the environment.	This article
C6.3	Distance to High-Voltage Lines	Installations located too close to high-voltage lines may be subject to operational failures due to electromagnetic interference, jeopardizing the efficiency and safety of the installation	This article
C6.4	Distance to Flood Locations	Facilities located in areas at high risk of flooding can be inundated during natural disasters, jeopardizing the operational integrity of the facility as well as leaking hazardous waste into the environment.	[45]

Table 4 presents the evaluations of all the alternatives made by three experts in the study, taking into account the 19 criteria and using nine linguistic values. The linguistic decision matrix for all the alternatives is shown in Table 5.

Table 4. DM criteria evaluation with linguistic expressions.

	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C3.1	C3.2	C3.3	C4.1	C4.2	C4.3	C5.1	C5.2	C5.3	C6.1	C6.2	C6.3	C6.4
DM1	HI	VHI	BAI	AI	LI	VHI	LI	VHI	LI	HI	BAI	LI	VHI	BAI	BAI	HI	BAI	LI	CHI
DM2	VHI	VHI	AI	AAI	AI	HI	LI	VHI	BAI	VHI	BAI	BAI	HI	AAI	BAI	AAI	AI	BAI	VHI
DM3	VHI	CHI	BAI	AAI	AAI	VHI	LI	CHI	AI	CHI	AI	LI	AAI	AI	LI	HI	AI	BAI	CHI

Table 5. Linguistic decision matrix for all the alternatives.

A1	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C3.1	C3.2	C3.3	C4.1	C4.2	C4.3	C5.1	C5.2	C5.3	C6.1	C6.2	C6.3	C6.4
DM1	AAI	VLI	VLI	VHI	AI	AI	CHI	HI	CHI	VLI	VLI	AI	LI	AAI	LI	LI	CHI	HI	VHI
DM2	HI	VLI	LI	CHI	AI	HI	VLI	VHI	VHI	VLI	VLI	AAI	LI	HI	LI	LI	VHI	VHI	VHI
DM3	AAI	VLI	LI	VHI	AAI	AAI	LI	CHI	CHI	LI	VLI	HI	LI	VHI	VLI	VLI	CHI	HI	VHI
A2	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C3.1	C3.2	C3.3	C4.1	C4.2	C4.3	C5.1	C5.2	C5.3	C6.1	C6.2	C6.3	C6.4
DM1	BAI	LI	AI	VLI	VLI	LI	CLI	LI	VLI	BAI	BAI	LI	BAI	LI	AAI	LI	BAI	LI	BAI
DM2	BAI	BAI	AAI	LI	LI	LI	CLI	LI	VLI	BAI	BAI	BAI	BAI	LI	HI	BAI	LI	LI	LI
DM3	AI	BAI	HI	VLI	LI	VLI	LI	LI	VLI	AI	BAI	BAI	AI	LI	VHI	LI	BAI	VLI	LI
A3	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C3.1	C3.2	C3.3	C4.1	C4.2	C4.3	C5.1	C5.2	C5.3	C6.1	C6.2	C6.3	C6.4
DM1	LI	AI	LI	AI	AI	BAI	BAI	LI	LI	AAI	AI	VLI	AI	LI	AI	AI	BAI	VLI	BAI
DM2	BAI	AAI	VLI	AI	AAI	BAI	BAI	LI	LI	BAI	BAI	LI	BAI	VLI	HI	BAI	AI	VLI	VLI
DM3	LI	HI	LI	AAI	AI	AI	AI	VLI	CLI	HI	HI	LI	AI	LI	AAI	AI	AAI	VLI	VLI
A4	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C3.1	C3.2	C3.3	C4.1	C4.2	C4.3	C5.1	C5.2	C5.3	C6.1	C6.2	C6.3	C6.4
DM1	VLI	AAI	HI	LI	LI	VLI	AAI	VLI	CLI	LI	VLI	LI	VLI	BAI	LI	HI	HI	VHI	AAI
DM2	LI	AAI	HI	LI	LI	LI	BAI	LI	VLI	VLI	LI	VLI	LI	LI	VLI	VHI	VHI	VHI	HI
DM3	BAI	HI	AI	VLI	VLI	CLI	AI	VLI	CLI	LI	BAI	LI	LI	AI	LI	VHI	VHI	VHI	AI

The combined IVN decision matrix values for all the alternatives were calculated by determining the criterion weights of the lower and upper values of the T, I, and F. Table 6 displays only the lower and upper T, I, and F values of the alternatives for the C1, C2, and C3 criteria.

Table 6. IVN decision matrix.

		A1	A2	A3	A4			A1	A2	A3	A4			A1	A2	A3	A4
C1.1	TL	0.583	0.482	0.382	0.345	C2.1	TL	0.786	0.282	0.550	0.321	C3.1	TL	0.623	0.216	0.482	0.522

	TU	0.684	0.566	0.482	0.446		TU	0.892	0.382	0.616	0.422		TU	0.778	0.317	0.566	0.607
	IL	0.518	0.578	0.478	0.432		IL	0.214	0.377	0.618	0.417		IL	0.269	0.209	0.578	0.578
	IU	0.618	0.679	0.578	0.534		IU	0.316	0.478	0.718	0.518		IU	0.378	0.317	0.679	0.679
	FL	0.417	0.518	0.618	0.655		FL	0.214	0.718	0.450	0.679		FL	0.377	0.784	0.518	0.478
	FU	0.518	0.618	0.718	0.755		FU	0.316	0.819	0.550	0.779		FU	0.502	0.885	0.618	0.578
C1.2	TL	0.250	0.412	0.583	0.583	C2.2	TL	0.550	0.312	0.550	0.321	C3.2	“	0.755	0.350	0.321	0.282
	TU	0.350	0.512	0.666	0.684		TU	0.616	0.412	0.616	0.422		TU	0.868	0.450	0.422	0.382
	IL	0.350	0.508	0.554	0.518		IL	0.618	0.407	0.618	0.417		IL	0.271	0.450	0.417	0.377
	IU	0.450	0.608	0.655	0.618		IU	0.718	0.508	0.718	0.518		IU	0.379	0.550	0.518	0.478
	FL	0.750	0.588	0.417	0.417		FL	0.450	0.688	0.450	0.679		FL	0.245	0.650	0.679	0.718
	FU	0.850	0.688	0.518	0.518		FU	0.550	0.789	0.550	0.779		FU	0.350	0.750	0.779	0.819
C1.3	TL	0.312	0.583	0.321	0.623	C2.3	TL	0.583	0.321	0.482	0.254	C3.3	TL	0.825	0.250	0.296	0.181
	TU	0.412	0.666	0.422	0.712		TU	0.666	0.422	0.566	0.355		TU	0.930	0.350	0.396	0.282
	IL	0.407	0.554	0.417	0.502		IL	0.554	0.417	0.578	0.293		IL	0.175	0.350	0.324	0.193
	IU	0.508	0.655	0.518	0.604		IU	0.655	0.518	0.679	0.401		IU	0.277	0.450	0.434	0.298
	FL	0.688	0.417	0.679	0.377		FL	0.417	0.679	0.518	0.746		FL	0.175	0.750	0.704	0.819
	FU	0.789	0.518	0.779	0.478		FU	0.518	0.779	0.618	0.846		FU	0.277	0.850	0.805	0.919
		-	-	-	-			-	-	-	-			-	-	-	-
		-	-	-	-			-	-	-	-			-	-	-	-
		-	-	-	-			-	-	-	-			-	-	-	-

Subsequently, the sp_n and npn values were obtained, as shown in Table 7, where the PDA and NDA values and weights were multiplied neutrosophically. The equations between 5 and 9 were used to find the values.

Table 7. sp_n and np_n values.

	TL	TU	IL	IU	FL	FU
			sp_n Table			
A1	−1.403	9.694	30.670	32.287	−0.657	11.316
A2	−6.603	3.220	31.980	33.315	4.795	15.677
A3	−4.318	5.545	33.562	34.628	2.407	13.731
A4	−6.002	4.071	30.750	32.331	4.145	15.191
			np_n Table			
	TL	TU	IL	IU	FL	FU
A1	1.403	−9.694	30.670	32.287	16.137	8.416
A2	6.603	−3.220	31.980	33.315	10.685	4.054
A3	4.318	−5.545	33.562	34.628	13.073	6.000
A4	6.002	−4.071	30.750	32.331	11.336	4.540

The normalized values for sp_n and np_n were computed for all the alternatives using Equations (10) and (11) after normalizing the values. The evaluation score was calculated using Equation (12), taking into account all the alternatives. The alternatives are displayed from best to worst based on the descending order of these scores. Accordingly, it appears to be in first place with the highest alternative score of 0.717. Alternative four appears to be in last place, with its smallest alternative score of 0.679.

Equations (10) and (11) were used to compute the normalized values for $sp_n$and np_n, respectively, for all the alternatives. The evaluation score was calculated using Equation (12), taking into account all the alternatives. The alternatives are displayed in Table 8 from best to worst based on their scores, with alternative one having the highest score of 1802. Alternative two came in second place, with a score of 1791, while alternatives three and four received the lowest scores among the four options, with a score of 1767.

Table 8. Scores and rankings.

ALT	TL	TU	IL	IU	FL	FU	Score	Ranking
A1	0.497	0.521	0.443	0.441	0.468	0.483	1802	1
A2	0.486	0.507	0.441	0.439	0.478	0.492	1767	3
A3	0.491	0.512	0.439	0.437	0.474	0.488	1791	2
A4	0.488	0.509	0.443	0.441	0.477	0.491	1767	4

The study analyzed the location of a MW disposal facility using the IVN set method. To address data uncertainty, neutrosophic sets are preferred. Interval-valued fuzzy sets are particularly useful as they allow decision-makers to use interval parameters and explain different opinions. The IVN fuzzy EDAS method guides decision-makers using neutrosophic sets and addresses the incompleteness, uncertainty, and inconsistency in knowledge. In this decision problem, the experts discussed and eliminated 40 potential alternatives in the preliminary stages. However, when considering these four alternatives using a heuristic approach based on experience, a common decision could not be reached. Therefore, it was expected that the scores would be very close.

4. Conclusions

In today's world, rapid urban population growth and outbreaks of infectious diseases pose challenges for effective MWM, especially in large metropolitan cities like Istanbul. The existing waste incineration facility in Istanbul, being the first and only facility operating at full capacity in Turkey, plays a crucial role in managing MW without harming the environment or public health. The selection of a location for the planned second centralized MW incineration facility entails a highly strategic decision-making process and involves numerous uncertainties. The choice of a new MW disposal facility location requires comprehensive expertise in various social and environmental fields, such as construction cost, land use, soil science, seismic risk, engineering, hydrogeology, topographic features, transportation infrastructure, and economics. This research comprehensively addresses these uncertainties, enabling the selection of the most suitable facility location.

This study evaluated potential MW disposal sites in Istanbul using IVN fuzzy EDAS. The assessment of alternatives was conducted through a hierarchical framework of criteria. The study employed neutrosophic sets to assist decision-makers in addressing the gaps, uncertainties, and inconsistencies in this complex strategic decision problem. To tackle data ambiguity, this study introduced the application of neutrosophic sets, expanding conventional MCDM methods. The use of fuzzy sets with interval values allowed for the inclusion of interval parameters and the expression of different opinions. This not only facilitated the study for decision-makers but also enabled successful decision-making in an uncertain environment.

Based on the ratings of three experts, this study evaluated 19 criteria across six dimensions. The experts assigned higher importance to dimensions such as proximity to settlement areas and disaster and emergency preparedness. This emphasis reflects the unique challenges posed by Istanbul's densely populated urban landscape, where the proximity of waste disposal facilities to residential areas is a prominent concern. Moreover, Istanbul's location makes it vulnerable to seismic activity and other natural disasters because of its proximity to fault lines and bodies of water. Therefore, it is crucial to focus on disaster risk mitigation measures. When evaluating disposal facility alternatives, certain criteria emerged as particularly significant. Factors to consider when selecting a location for waste disposal include proximity to flood-prone areas and residential zones, logistical considerations, and the protection of water resources and educational institutions. The disposal of MW poses significant risks to public health, environmental integrity, and the well-being of vulnerable populations. This is particularly true in large cities like Istanbul, where logistical challenges exacerbate these dangers. Our analysis revealed that factors directly related to health and disaster resilience were prioritized over those of lesser relevance, such as land costs, topographical features, proximity to landfills, and distance to high-voltage lines. It is important to note that subjective evaluations were excluded from the evaluation process. The analysis underscores the importance of prioritizing the factors directly related to health and disaster resilience over those of lesser relevance.

The study concluded that Pendik was the most appropriate location for MW disposal based on the highest score among the alternatives assessed. The alternatives were ranked from best to worst based on their scores, with Pendik being the top choice with a score of 1802. Arnavutkoy was the second-best option with a score of 1791, while Silivri and Sile received the lowest scores among the four options, with a score of 1767. The experts evaluated numerous potential locations and eliminated 40 alternatives in the preliminary stages. Based on this research, it can be concluded that these four alternatives have similar importance values since many other options were discarded early on. In conclusion, our study emphasizes the importance of prioritizing health considerations and disaster resilience when evaluating MW disposal facilities, especially in urban settings with complex socio-geographic dynamics like Istanbul. Our research aims to inform evidence-based decision-making for sustainable waste management practices in densely populated urban environments. We systematically scrutinized diverse criteria and weighed their relative significance.

The study presents a novel method for addressing MW disposal siting issues. The method's effectiveness and applicability demonstrate its potential for addressing similar facility location problems with high levels of uncertainty. The decision model has been applied in various settings, such as landfill facilities, municipal solid waste recycling facilities, composting facilities, drinking water treatment facilities, and wastewater treatment facilities. In future studies, the decision model could take into account causal relationships between the criteria and consider adding new criteria, particularly those related to sustainability. In addition, the method can be compared with other fuzzy sets of the neutrosophic set or MCDM methods, such as CODAS, TOPSIS, and AHP. Hybrid approaches could also be developed for selecting sites for MW disposal facilities. Artificial intelligence and machine learning can be used to incorporate expert opinions in new models, particularly for uncertain criteria, to facilitate faster and more objective decision-making.

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