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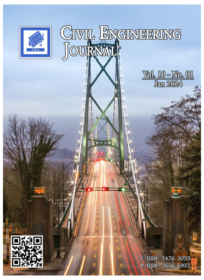

Application of GIS Models in Determining the Suitable Site for a Solid Waste to Energy Plant in an Urban Area

Ali Basha [1*], Ahmed Salem [1], Wael Mostafa [2], Magda H. Farhan [1]

[1] *Department of Civil Engineering, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, 33511, Egypt.*

[2] *Department of Geography, Faculty of Arts, Kafrelsheikh University, Kafrelsheikh, 33511, Egypt.*

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Abstract

This paper deals with the establishment of a solid waste-to-energy plant that significantly reduces the volume of solid waste and produces electricity at the same time. Thirteen criteria have been identified to locate the station based on environmental, economic, and social factors to avoid its negative impacts. These criteria were addressed by combining a Multi Criterion Decision Making (MCDM) method based on the GIS software. This study aims to establish a MCDM system based on the classical AHP and validated by the fuzzy AHP method. The findings revealed that using the classical AHP and fuzzy AHP methods, there was no significant difference in decision-making between the two methods. The importance of the criteria under study has been identified based on the judgments of experts; a questionnaire was designed and conducted electronically, which was collected with the help of a weighted overlay GIS model. This technique combines multiple reclassified data in ArcGIS 10.8 software to overlay criteria layers with different weights to create a composite map of suitability categories across the study area. The outcomes revealed that 96.76% of the study area is unsuitable for establishing the station, 1.36% is moderately suitable, and 0.04% is only very suitable for station site selection.

Keywords: Waste to Energy; GIS; MCDM; Classical AHP Method; Fuzzy AHP Method; Kafrelsheikh; Solid Waste.

1. Introduction

Population expansion, globalization, and technological advancement have sped up the dynamics of urbanization processes in emerging nations, which has increased the amount of Solid Waste (SW) produced. As a result, issues with Solid Waste Management (SWM) remain an important focus of international environmental policy for long-term development [1, 2]. Due to that and limited space, local governments and planners face significant difficulty managing solid waste [3]. Spreading rubbish is a recurring environmental concern in the Arab Republic of Egypt, with an estimated 40% of the total garbage produced not being collected; only a small part of the collected waste is treated and disposed of in places with a generally acceptable level of environmental management. Without applying environmental safeguards, the remainder is dumped on public lands alongside waterways, roads, railways, etc. Unintentional trash disposal aids in the spread of illness, the deterioration of the environment, and the contamination of surface and ground waters [4]. According to a prior study, the trash generation rate in Egypt's Kafrelsheikh Governorate was 0.82 kg per person daily at a rate of 950,000 tons of garbage every year [5].

The construction and the SW power plant's functioning is one of the recommended methods for waste disposal, rising energy demand, and restricts on landfilling [6, 7]. Several nations in Europe, Asia, and America have recently changed

* Corresponding author: ealibasha@eng.kfs.edu.eg

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their primary method of garbage disposal from landfilling to converting waste into energy [8, 9]. Waste to Energy (WTE) is more effective at managing waste than landfills and composting because it has advantages such as requiring less space, reducing waste volume, and producing power [10].

Numerous social and environmental problems are associated with positioning facilities for waste conversion in appropriate locations and at maximum capacity. For instance, one of the major environmental difficulties is societal opposition and refusal to set up the station because of the smells, noise, and litter in the surrounding area [11]. Choosing a site for a particular activity necessitates a suitability analysis, considering various factors depending on the activity type. The primary goal of suitability analysis is to determine the best spatial layout for future land uses by categorizing different areas under study according to their appropriateness for a particular activity [12]. The MCDM techniques provide a powerful vehicle to facilitate and hasten any siting process and provide a workable planning and policy-making solution when integrated with GIS. They become stronger because of the facilities they provide for obtaining satellite images, maps, and aerial images, analyzing them, and displaying them in the form of graphs, maps, and reports [13–15].

After consultation and discussions with regional experts and reviewing the relevant literature, this research identified 13 criteria covering environmental, economic, and social concerns commensurate with the nature of the study area. Numerous factors are taken into account and given values in MCDM analysis in order to determine the corresponding relative weighted values. The fuzzy AHP approach has been validated by the AHP, a typical MCDA technique that determines the relative importance of each criterion by pairwise comparison of many criteria and a multilevel hierarchical structure.

Many previous studies have used different techniques and approaches to determine the location of WTE plants; for example, Abushammala et al. [16] used the MCDM method and GIS software to process the criteria and the Weighted Overlay method to calculate the weights of the criteria. In another study, Chullamon & Skolpap [17] used geographic information systems and weighted average (WA) technology. In another study, Yalcinkaya & Kirtiloglu [18], the authors used fuzzy AHP and GIS to determine the station's location. Others, Meng et al. [19], used the single-valued nutrosophic sets and combined them with decision-making and trial evaluation laboratory-analytical network processes (DANP) and GIS to determine the impact of the criteria and calculate their weights. In many of the studies conducted on determining the location of a landfill relevant to our research topic, the authors used techniques of MCDM, GIS, AHP, and remote sensing [20–25]. Which indicates the widespread use of the MCDM method and its integration with GIS in determining locations due to its ability to simplify and facilitate the case, provide information, and not take a longer time.

This study aims to develop guidelines for constructing a new WTE plant and suggest a model by considering the environmental, economic, and social suitability using the decision-making technique based on GIS software. Since there is not a functioning SW power plant in Egypt, Kafrelsheikh Governorate was chosen as a case study.

1.1. Study Area

The current study focuses on Kafrelsheikh Governorate as a representative region of Egypt's populated rural and urban sectors, the most densely populated country in the Middle East and North Africa region. Kafrelsheikh Governorate is located in the north of Egypt, between the two branches of the Nile River in the north-western part of the Nile Delta, with an extension of 85 km (Figure 1). It is bounded to the north of the Mediterranean Sea with an extension of 100 km, between latitudes 31° 37` N and 31° 20` E with an elevation ranging from -26 to 138 m (Figure 3a). It is administratively divided into ten cities (Figure 1). According to the Central Agency for Public Mobilization and Statistics, Kafrelsheikh Governorate has a population of 3,362,185 and an area of 3,738.48 km² [25] (Table 1; Figure 2). The governorate experiences a Mediterranean climate, Annual rainfall is between 140 and 250 mm, and the predominant winds are from the west and northwest. The governorate produces 30% of the rice crop in Egypt. It has the largest fish farm in the Middle East, in the Ghalioun pond. It enjoys various tourist activities, recreational, religious, and archaeological. The governorate has a diverse representation of socioeconomic strata.

Table 1. The general authority for urban planning classifies the Kafrelsheikh Governorate's lands using Support Vector Machine learning (SVM) (https://earthexplorer.usgs.gov/)

Classification	Area (km²)	Percentage (%)
Agricultural lands	2642.89	70.69
Land availability (bare land)	119.79	3.21
Fish farm	312.83	8.37
Natural vegetation	181.01	4.84
Urban (sensitive land)	249.95	6.69
Surface water (Water bodies)	231.83	6.20
Total	3738.48	100

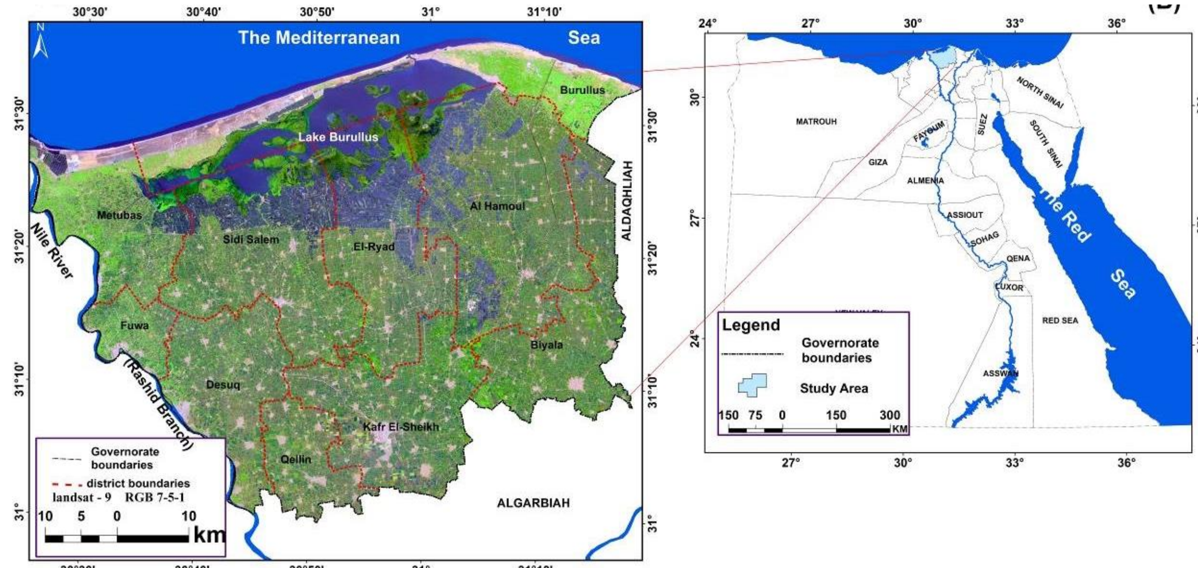

Figure 1. Location of Kafrelsheikh Governorate (the red lines show the division of towns/cities in Kafrelsheikh Governorate) [26]

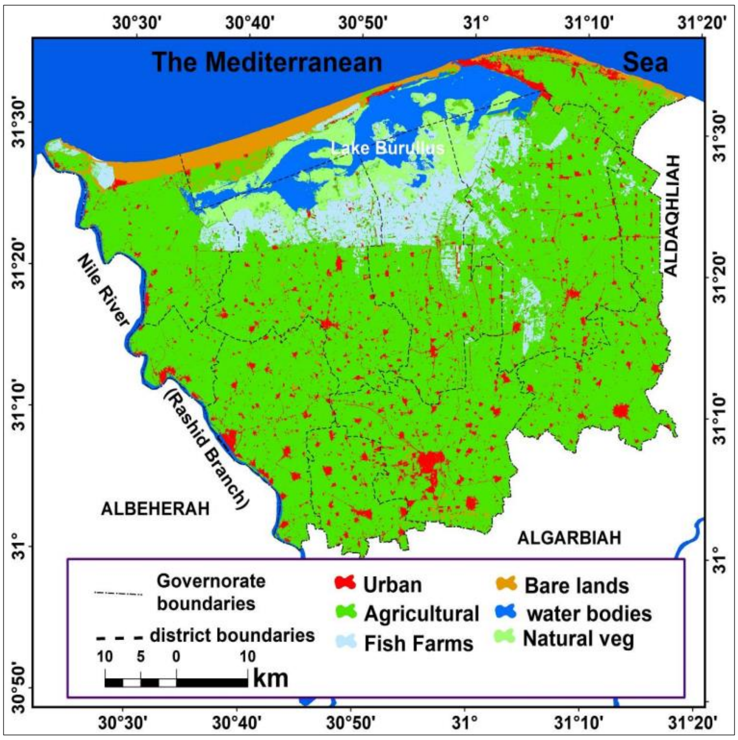

Figure 2. Land cover map using Support Vector Machine learning (SVM) classification algorithm of Kafrelsheikh Governorate (https://earthexplorer.usgs.gov/)

2. Production of Solid Waste

Solid waste is the unwanted or worthless solid materials created by a combination of commercial, industrial, and residential activity in a specific location. It can be divided into groups based on its origin (home, industrial, commercial, agricultural, etc.) and its contents according to their hazardous potential (toxic, non-toxic, flammable, radioactive, infectious, etc.). Typically, all garbage produced in a community is referred to as solid waste [27].

A previous study conducted a field experiment to identify and characterize solid waste and the percentage of waste components in the governorate. The proportions were as follows: Paper 6.24%, Plastic 11.76%, Glass 1.23%, Metals 3.97%, Textiles 2.30%, Food 66.01%, Wood 0.14%, and Others 8.35% [5]. This allows more than one method to operate the station, such as burning and Anaerobic Digestion (AD).

Waste-to-energy (WTE) is one of the most effective ways to dispose of waste [28]. The fundamental benefit of WTE is that it not only benefits the waste management industry by providing an effective means of final disposal but also benefits the energy industry by heating or providing electricity. WTE processes result in products like transportation fuels, synthetic natural gas, chemicals, ferrous and non-ferrous metals, and energy. In addition, it emits less carbon dioxide (CO_2) and greenhouse gases (like methane) than landfills.

The production of solid waste is one of the main factors endangering environmental quality worldwide. Accordingly, integrated waste management systems must be considered to achieve sustainable development. The Kafrelsheikh Governorate produces 2625 tons/day of waste (SWM in Kafrelsheikh Governorate 2023) distributed over cities according to Table 3. The cities with the highest waste production are the city of Desuq, followed by the city of Kafrelsheikh, the capital of the governorate. There is currently no landfill for the governorate, but plans are underway to establish a sanitary landfill in the city of Burullus. Waste collected from cities is sent to the controlled landfill in Metubas City, the Tal al-Mutair landfill in Desuq City, and the Qellin landfill. The volume of trash in the controlled Metubas landfill was 1750 tons/day, the Tal Al-Mutair landfill had 676 tons/day, and Qellin had 199 tons/day. There are two factories for solid waste recycling in the governorate, Biyala and Sidi Salem, for producing fertilizers with a production capacity of 800 tons/day (Table 2).

Table 2. The amount of waste that is recycled in Kafrelsheikh Governorate (SWM, Kafrelsheikh Governorate 2023)

Amount of waste recycled	Recycling Entity	Quantity directed to landfills	Amount of waste left after recycling	Recycling Methods
382 (ton/day)	Biyala Solid Waste Plant Design Power: 420 ton/day Operating Capacity: 400 ton/day amount of fertilizer: 114 ton/day RDF: 57 ton/day	76 (ton/day)	2042 (ton/day)	• Use of organic material for the production of organic fertilizer. • Separate any components with high heat content to be used as coal replacement fuel in cement plants. • Separating and reusing iron and sorting other ingredients that have economic importance such as plastic, cartoon, glass and residual materials refuse and are transported to landfills.
346 (ton/day)	Sidi Salem Solid Waste Plant Design Power: 420 ton/day Operating Capacity: 400 ton/day Amount of Fertilizer: 104 ton/day RDF: 52 ton/day	69 (ton/day)		

All population forecasting techniques indicate that the population will certainly increase in the coming decades with a population growth rate of 1.62%. The population of Kafrelsheikh governorate reached 3,695,336 people in 2023 and the population will increase to 4,339,563 by 2033 according to the Equation 1 [29].

$$PN = PO\ (1+R)^N \tag{1}$$

where: PN = predicted population, PO = the current population, R = population growth rate, N = Interval between the two censuses. Consequently, the rate of waste generation will increase to 3,559 tons/day by 2033 according to Table 3. This is a major reason for this study and work on the installation of such plants to reduce the risk of increasing waste and for sustainable development.

Table 3. The latest Population 2017 [30], Projected Population on 2023. Quantity of SW there is generated in urban areas 2023 (SWM, Kafrelsheikh Governorate 2023), Projected SW in 2033 and the distance to the landfills

City	Population 2017	Population 2023	Population 2033	Quantity of waste (ton/day) 2023	Expected Quantity of waste (ton/day) 2033	Distance to landfills (km)
Kafrelsheikh	623510	686488	806167	417	661	125
Al hamoul	289375	317687	373071	243	306	125
El Ryad	186159	204100	239682	130	197	60
Burullus	235051	259358	304573	200	250	67
Biyala	297455	327146	384179	235	315	125
Desuq	546671	600945	705711	527	579	20
Sidi Salem	437667	479594	563204	303	462	60
Fuwa	179002	197682	232145	149	190	15
Qellin	265054	290876	341586	199	280	40
Metubas	302241	331460	389245	222	319	40
Total	3362185	3695336	4339563	2625	3559	1082

The amount of waste left after recycling is 2042 tons/day. Waste reduction is vital because it will reduce waste volume and disposal while addressing energy needs. Because significant levels of solid waste severely threaten pollution and environmental degradation, waste reduction is essential.

3. Research Methodology

3.1. Choosing Decision Levels (Objectives, Standards) and Practical Considerations

All research on the positioning of WTE plants shows that different countries' standards for decision-making follow common objectives, including environmental, economic, and social desirability. These standards differ from one country to the next, or even from region to region within the same country [31].

The aim of site selection is to find the best location with the least detrimental effects on the environment and other natural resources, minimize financial expenditures, and have the best qualities from an engineering standpoint. As a result, focused regional studies are required to determine the local potential and confirm the energy required to build a WTE plant. The Egyptian laws or regulations do not govern the site selection criteria and environmental effect assessment of trash WTE plants. This study chose a sub-criterion after reviewing previous studies and the conditions of the study area and speaking with experts. Thirteen sub-criteria were classified to choose the location of the WTE plant. Each of these criteria includes different aspects.

Relevant in this study to detect the location of the WTE station in Kafrelsheikh Governorate, a questionnaire was prepared to determine the importance of these criteria, measured by a particular scale [32]. It ranges from 1 to 9 according to the AHP method. Many experts from academia, including the Ministry of Housing, Utilities, Urban Communities and Planning, Environment, Electricity, and Energy, participated. In order to determine the importance of the following criteria.

3.1.1. Distance to Sensitive Land Uses

It is difficult to avoid the noise, odor, and emissions of a WTE plant when operating. The plant's emissions are detrimental to human health; consequently, the plant location should be located far from populated areas and popular tourist destinations [10, 33]. As a result, the greater the distance between sensitive land uses (such as homes, hospitals, schools, tourist attractions, shops, mosques, military areas, etc.) and the location of the facility, the better to reduce harmful effects. Finding ideal locations for the plant also considers the regions and plots set aside for future development. The percentage of sensitive areas in the study is 6.69% (Table 1). Based on the previous literature review, a buffer zone of at least 500 meters should be imposed on sensitive land in the lands of the governorate [10, 16, 33].

3.1.2. Distance from Agricultural Land

The site of the plant should be isolated from the agricultural area to prevent pollution of edible plants and crops. The larger the space between the plant site and agricultural land, the more suitable the area becomes. A suitable distance must be maintained between the agricultural areas and the location of the station, especially since Kafrelsheikh Governorate is covered by 70.69% of the vegetation lands of the governorate. Based on the previous literature review, a buffer zone of at least 500 meters should be imposed around agricultural land [16].

3.1.3. Distance to Surface Water

This criterion is crucial from the standpoint of environmental concerns because it excludes places that are fewer than 1,000 meters from surface water. The percentage of water bodies on the governorate's lands is 6.20%.

3.1.4. Distance to Landfills

An integral part of the economic and environmental issues of its integrated solid waste management system, such as fuel consumption and pollution when transporting solid waste [33]. The transportation of solid waste considerably affects the operating costs of the facility, directly affecting its economic viability. To cut transportation costs, it is essential to locate the plant close to a potential supply of solid waste [10]. Therefore, to save on transportation costs and pollution, it is important to construct a plant adjacent to landfills that receives large quantities of solid waste regularly. The shorter the distance between the station and the waste dumps, the greater the suitability.

3.1.5. Distance to the Electricity Grid

To make it simple to feed the grid with the generated electricity, the facility should be located close to the existing electrical system [33, 34].

3.1.6. Distance to the Road Network

To provide simple access and efficient solid waste transportation to the plant, it is necessary to choose a plant site near major roadways [33–35]. Transportation of solid waste accounts for a sizable amount of the power plant's operational costs, which may impact the plant's economic viability [33, 36]. This proposed method will avoid developing station-specific routes. Therefore, the precise location must be close to the current highways and main roads. It is also considered necessary to move away from the roads by at least 300 meters as a buffer zone to avoid the visual impact of the building and unpleasant odors. A distance closer to the current roads is given more weight. The governorate is linked by a road network of 875 km, according to the Egyptian Ministry of Transport (General Authority for Roads, Bridges, and Land Transport).

3.1.7. Elevation

Elevation directly affects the trucks' fuel efficiency; hence, the site should be in a low elevation area. Access is more challenging as the altitude increases and transportation costs increase. As a result, expected, site locations that have higher elevations are given less weight. Based on the study of the area, it was found that the height ranges between -38 m to 133 m (Figure 3-a) above sea level.

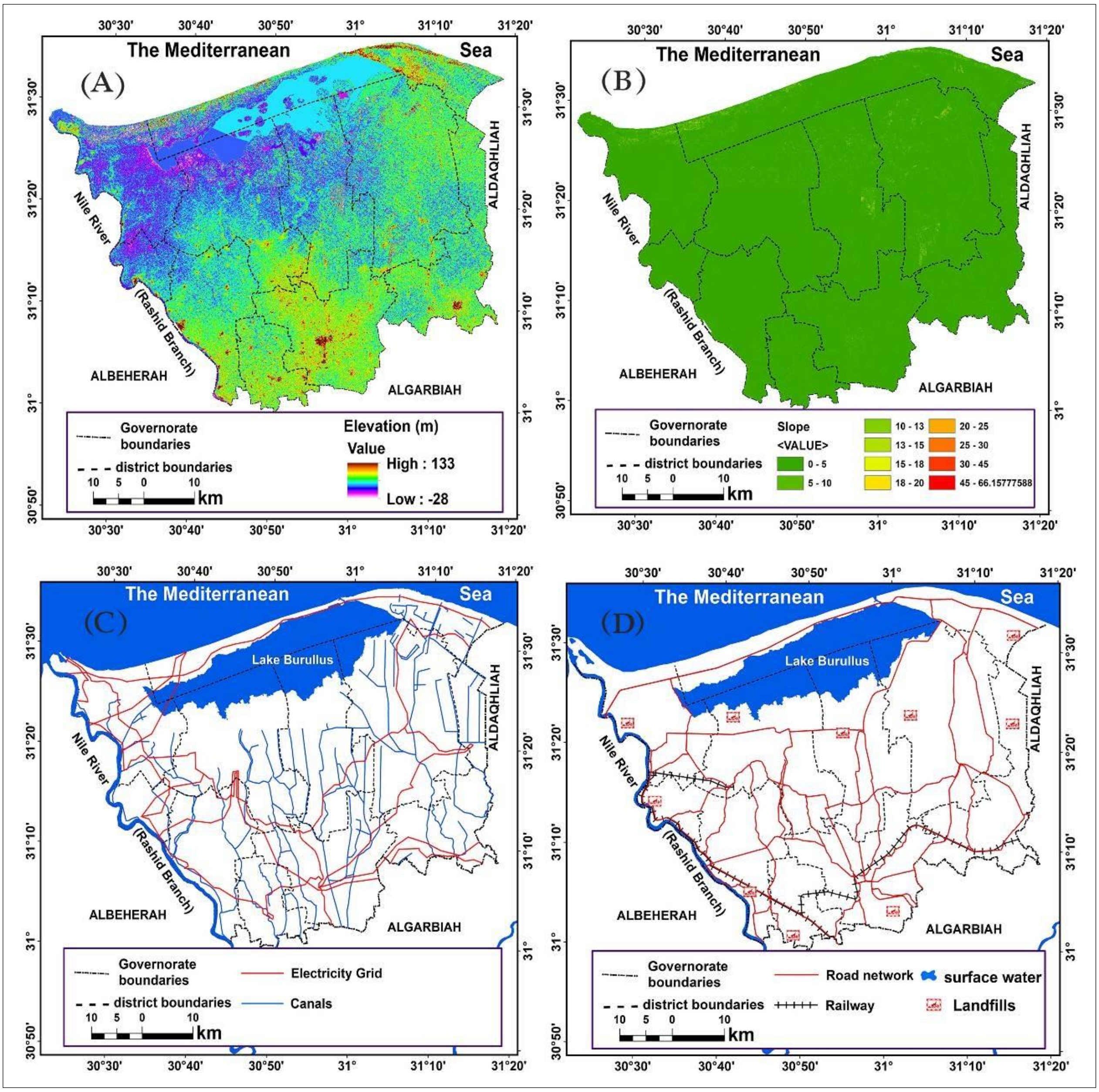

Figure 3. (a) Elevation; (b) Slope; (c) Electricity grid, main canals, and the river; (d) Surface water, road network, railway, and landfills in the study area of Kafrelsheikh Governorate

3.1.8. Terrain Slope

Flatter places are more appropriate for creating the plant because the technical viability of a region for establishing an industrial facility declines with rising slopes [33, 35]. The slope of the terrain is an economic factor in building a plant. Sloping lands are more challenging to access.

3.1.9. Railway Line

Despite the city's tiny railway line length, both sides of the centerline must have a 300 m buffer zone. To mitigate the harmful effects of odors and emissions and to maintain the aesthetic appearance, the longer the distance between the railways and the location of the station, the better. The length of the railways in the governorate reached 125 km, according to the Ministry of Transport (the National Authority for Egyptian Railways).

3.1.10. River and Main Channels

It is necessary to exclude distances of less than 1,000 meters from the Nile River, represented by the Rashid branch and canals, to reduce the risk of water pollution that these plants can cause, as Egypt relies entirely on the Nile River water for drinking and irrigation of crops.

3.1.11. Landfill

An engineered landfill is a location where solid waste is treated scientifically. Therefore, having a suitable site for the disposal of residual waste after processing operations is crucial [33]. Transporting solid waste accounts for a significant amount of the plant's operating costs, which has an immediate impact on the viability of the facility [10]. Therefore, in order to reduce transportation costs and pollution, it is desirable to construct a plant close to landfills that regularly collects large amounts of solid trash [16].

3.1.12. Wind Direction

The direction of the wind is one of the essential criteria in choosing the location of the plant. The smell from the station can disturb residents who live downwind. According to National Meteorological Agency reports, the predominant winds are from the west and northwest.

3.1.13. Land Availability

The location of the facility should be close to new or abandoned regions or unused land in the study area and away from areas earmarked for future development or land currently occupied. This criterion was not classified, as the main objective of the research was limited to obtaining plots of land that were not developed or available for construction [16, 34], as shown in Figure 2.

3.2. Limitations of Standards

Determining the permissible distance from the station site requires consideration of government regulations, potential environmental hazards, public health, and economic assessment of each criterion, restrictive criteria, and suggested insulating values for the study area, as depicted in Table 4 [10, 11, 33, 38–40]. After reviewing the literature and consulting with experts, the evaluation criteria were set on a scale of 0 to 10, with 0 being the limited area (not subject to investigation), 1 being the least preferable, and 10 being the most preferred area [33, 37]. In ArcGIS 10.8, this scale is utilized to evaluate low and medium, prior to them being combined with the MCDM approach used for all other criteria. Highly acceptable locations for each criterion are identified. In addition to the criteria's buffer zones and appropriateness levels.

Table 4. Details and grade values for the ultimate criterions

Criteria	The Restricted dimensions	1	2	3	4	5	6	7	8	9	10
Distance to sensitive land uses	< 500 m	> 500	200-meter intervals spaced equally								> 2300
Distance from agricultural land	< 500 m	500–700	200-meter intervals spaced equally								> 2300
Distance to surface water	< 1000 m	> 1000	100-meter intervals spaced equally								> 1900
Distance to landfills	> 25,000 m	25,000–22,500	Spans of 2500 m spaced evenly								< 2500
Distance to the electricity grid	> 200 m	> 9000	Spans of 1000 m spaced evenly								1000–200
Distance to the road network	< 300 m	> 2700	Spans of 300 m spaced evenly								<300
Elevation	>360 m	360	Spans of 40 m spaced evenly								-40 - 40
Terrain slope	> 45	> 30–45	25–	20–	18–	15–	13–	10–	5–10		< 5°
Railway Line	< 300 m	>300	Spans of 100 m spaced evenly								> 1200
River and main channels	< 1000 m	> 500	Spans of 200 m spaced evenly								> 2800
Landfill	Non-combustible elements found in municipal solid trash do not break down during incineration. Therefore, having an appropriate location to dispose of materials in the waste process is essential.										
Wind direction	The predominant wind direction in the region is primarily to blame for this.										
Land availability	Inhabited Land										Abandoned Land

3.3. Data Preparation

Data from several sources was used in this study. Maps showing sensitive land uses, standard current buildings (such as homes, businesses, hotels, factories, medical facilities, and schools), agricultural lands, water bodies, unoccupied lands, rivers, and water channels were obtained from free cloud coverage. Landsat-8, OLI with 11 spectral bands, Path 177, Row 38; (*https://earthexplorer.usgs.gov/*) satellite data on June 6, 2022. These data were freely available on the United States Geological Survey (USGS) website and projected to the Universal Transverse Mercator (UTM) with the WGS84 datum and projections system zone of 36N. The atmospheric correction was performed during pre-processing using ENVI-5.3 and Erdas Imagine 2022 software's packages before applying the machine learning supervised classification technique. The slope layer in degree measuring units was retrieved from the 12.5 spatial resolution Digital Elevation Model (DEM) using ArcMap 10.8 software (Figure 3-a). This DEM is downloaded using the USGS website.

The Ministry of Environment (Governorate Solid Waste Management) provided waste dump sites. While the roads and railways were provided by the Ministry of Housing, Utilities, and Urban Communities. The Egyptian Electricity Holding Company (Northern Delta Electricity Distribution Company) provided the electricity transmission lines and network data for the study area (Figure 3-c). The ArcMap 10.8 Euclidean distance tool was used to create raster surfaces for the vector parameters that reveal the radial distance from the element under analysis, such as sensitive areas, elevation, electricity networks, rivers/canals, road networks, etc. (Figure 3) Kafrelsheikh Governorate study degrees of suitability and buffer zones were determined for the standards (Table 4) to be reclassified from zero to ten values (Figure 4).

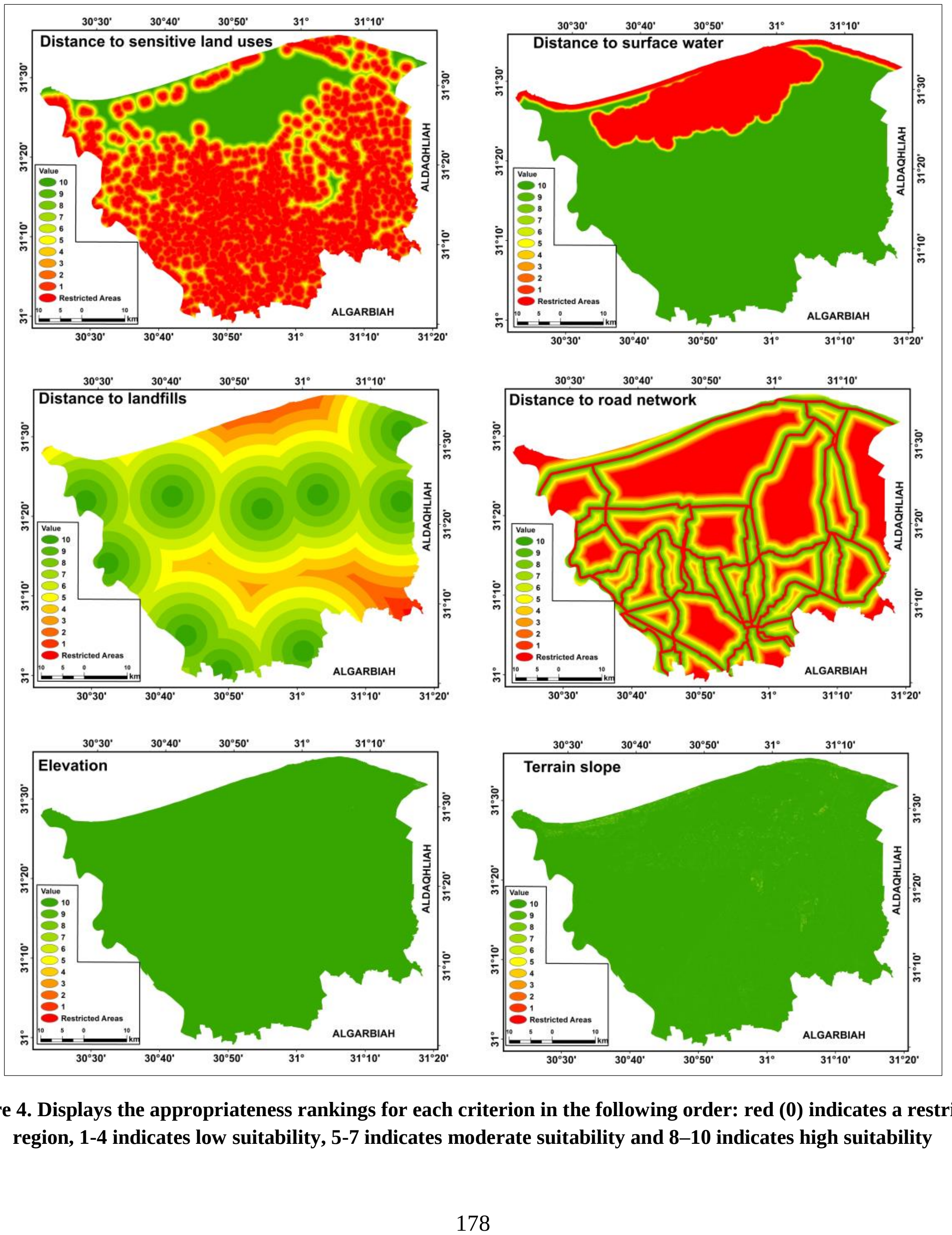

Figure 4. Displays the appropriateness rankings for each criterion in the following order: red (0) indicates a restricted region, 1-4 indicates low suitability, 5-7 indicates moderate suitability and 8–10 indicates high suitability

3.4. MCDA Approach using (AHP) and Fuzzy-AHP Method

Two different approaches AHP and fuzzy-AHP analytical techniques were used in this study (Figure 5) to predict the best site selection for the facility in the study area. By comparing the analysis results, the AHP and fuzzy AHP techniques were used to boost the validity and dependability of their research findings. To determine and calculate the importance of the criteria under study, a questionnaire was designed and conducted electronically based on the judgments of experts, in which 34 experts from the Ministry of Environment participated, represented by the solid waste department in the governorate, urban planning, the housing directorate in the governorate, the Ministry of Electricity, and academic circles. The questionnaire was completed according to Table 5 and Figure 6.

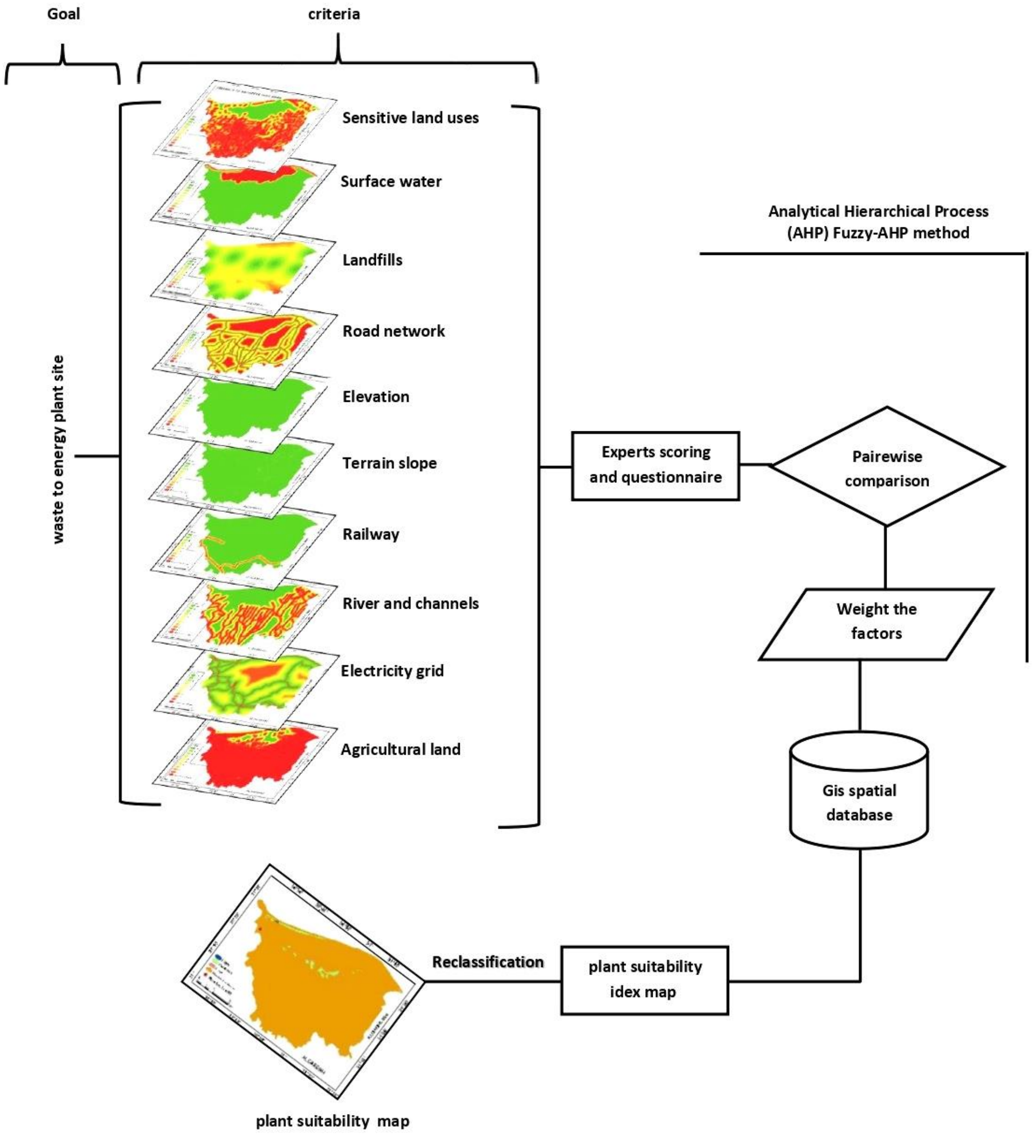

Figure 5. Flowchart of the methodology

Table 5. Questionnaire responses (https://forms.gle/y5SMm8UUyRWnfkvC6)

Importance measure	Values AHP	The number of responses									
		SL	LF	RN	EG	RC	SW	AL	E	TS	RL
Equally significant	1	0	0	0	0	1	1	5	14	20	8
Slightly significant	3	0	1	1	3	0	10	16	14	11	14
Strongly important	5	5	11	5	20	26	18	11	6	3	10
Very strongly important	7	14	15	23	11	5	3	1	0	0	2
Extremely important	9	15	7	5	0	2	2	1	0	0	0
Total		34	34	34	34	34	34	34	34	34	34
The weighted average of the responses on the significance value		4.6	6.6	6.9	5.5	5.4	4.7	3.6	2.53	2	3.4
Correction		7.5	6.5	7	5.5	5.5	4.5	3.5	2.5	2	3.5

SL=sensitive land; LF=landfills; RN=road network; EG=electricity grid; RC=River and channels; SW= Surface water AL=agricultural land; E=Elevation; TS=Terrain slope; RL=Railway Line.

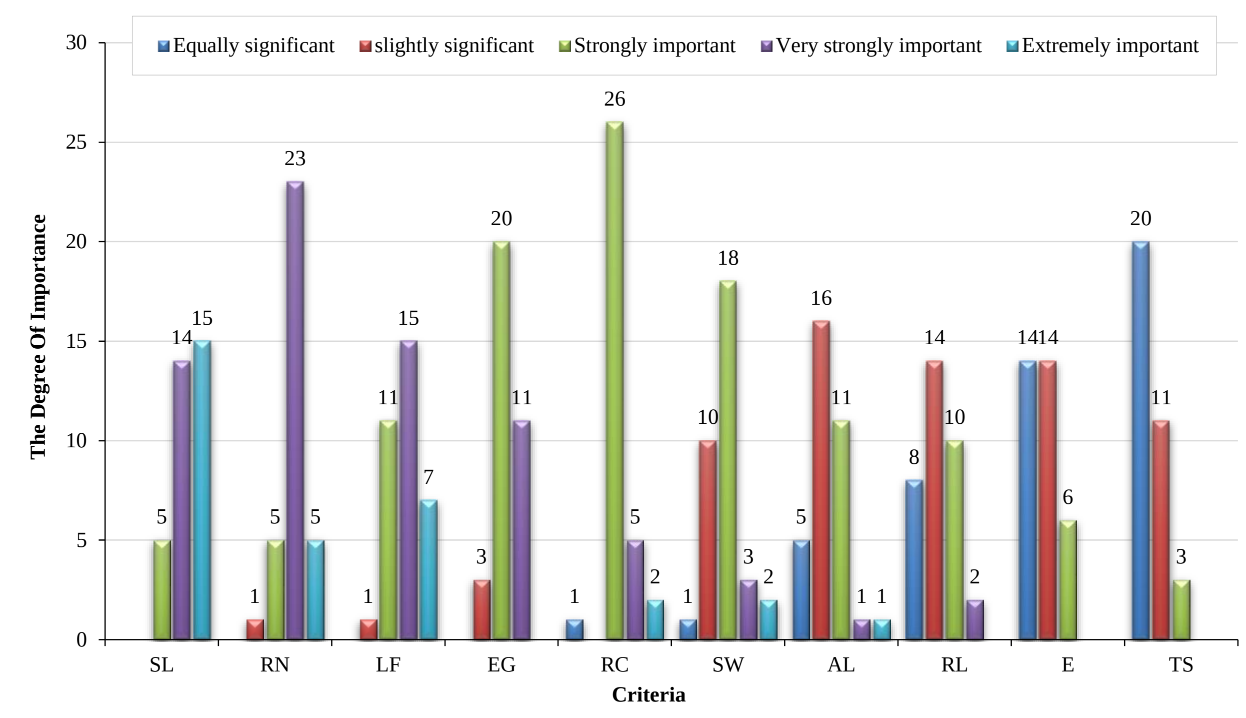

Figure 6. Questionnaire responses (https://forms.gle/y5SMm8UUyRWnfkvC6): SL=sensitive land; LF=landfills; RN=road network; EG=electricity grid; RC=River and channels; SW= surface water AL=agricultural land; E=Elevation; TS=Terrain slope; RL=Railway L.

3.4.1. Analytical Hierarchical Process (AHP)

The AHP is based on the n x n-dimensional criterion pairwise comparison matrix "A" [41]. To put this technique into practice, we must first describe the problem to be studied, then study the problem in terms of its variables, then rank options by making pairwise comparison matrices, and then get the findings of the sensitivity or feasibility analysis [42]. For the pairwise comparison of the criteria in Table 6, a scale from one to nine is employed, with one signifying equality of importance between the compared criteria and nine signifying the strong importance of one criterion over another [43]. The values must be added above the leading diagonal since Equation 2's reciprocity axiom will fill in the blanks in the cells below.

$$Matrix\ A = \begin{bmatrix} 1 & A12 & A13 & \dots\ A1n \\ 1/A12 & 1 & A23 & \dots\ A2n \\ 1/A13 & 1/A23 & 1 & \dots\ A3n \\ \vdots & \vdots & \vdots & \vdots \quad \vdots \\ 1/A1n & 1/A2n & 1/A3n & 1/An\ \ 1 \end{bmatrix} \tag{2}$$

Table 6. AHP scale by Saaty

Amount of Importance	Definition	Description
1	Equally significant compared to other things	Two factors that equally contribute to the goal
3	A little more significant than others	One criterion is moderately supported by assessment more so than the other.
5	Significantly more significant than others	In actuality, evaluation prefers one criterion in contrast to the other.
7	Really significantly more significant than others	In comparison, evaluation substantially favours one criterion over the other.
9	Significantly more significant than others	The most valid evidence favours one criterion above another.
2,4,6,8	Value separating neighbouring numbers	When to make a compromise
Opposite	Value for the comparison to the opposite	If one of the aforementioned integers exists between criterion i and criterion j, then j has a different value than i.

Equation 3 uses matrix A to construct the normalized matrix N, which averages each row to provide the weighted vector (W). This method's examination of the experts' opinions using the Consistency Ratio (CR) via Equation 4 is a crucial component [44]. For matrix A to be suggested as consistent, CR must be lower than 0.10 (10%). Matrix A should be re-evaluated if this ratio has a greater value. Prior to determining CR, the Consistency Index (CI), the Random Index (RI), and max must first be determined using Equations 5, 6, and 7, respectively.

$$Matrix\ N = \begin{bmatrix} \frac{A11}{\sum_{k=1}^{K=n} Ak1} & \frac{A12}{\sum_{k=1}^{K=n} Ak2} & \cdots & \frac{A1n}{\sum_{k=1}^{K=n} Akn} \\ \frac{A21}{\sum_{k=1}^{K=n} Ak1} & \frac{A22}{\sum_{k=1}^{K=n} Ak1} & \cdots & \frac{A2n}{\sum_{k=1}^{K=n} Ak1} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{An1}{\sum_{k=1}^{K=n} Ak1} & \frac{An2}{\sum_{k=1}^{K=n} Ak1} & \cdots & \frac{Ann}{\sum_{k=1}^{K=n} Ak1} \end{bmatrix} \begin{bmatrix} W1 \\ W2 \\ \vdots \\ Wn \end{bmatrix} Vectored\ Pesos\ W \tag{3}$$

$$CR = \frac{\text{CI}}{\text{RI}} \tag{4}$$

$$CI = \frac{\lambda max - n}{n-1} \tag{5}$$

$$RI = \frac{1.98 \times (n-2)}{n} \tag{6}$$

$$\lambda_{\max} = (\text{A}) \times (\text{W}) \tag{7}$$

It can also be calculated RI value from Table 7.

Table 7. The used Random Index (RI) values

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3.4.2. Fuzzy-AHP Method

Multiple authors have widely utilized the fuzzy AHP method, which has proven to be among the most effective assessment methods [45]. To rank the criteria and alternatives, fuzzy AHP determines the weight of the pairwise comparison matrix using the Triangular Fuzzy Number (TFN) scale. As shown in Table 8, the previously collected AHP scale is transformed into a fuzzification scale. In order to create the following pairwise comparison matrix, the scale of AHP transformed into that of TFN must be first [46, 47]. Lower, medium, and upper (L, m, u) are representations of the number of TFN, where l m u. It is regarded as non-fuzzy when l = m = u [48].

$$A = (aij)n * n \begin{pmatrix} (1,1,1) & (L12, M12, U12) & .. & (L1n, M1n, U1n) \\ (L21, M21, U21) & (1,1,1) & .. & (L2n, M2n, U2n) \\ \vdots & \vdots & .. & ; \\ (Ln1, Mn1, Un1) & (Ln2, Mn2, Un2) & .. & (1,1,1) \end{pmatrix} \tag{8}$$

In which $\text{aij} = (\text{Lij,Mij,Uij}) = \text{aij-1} = \left(\frac{1}{\text{uij}}, \frac{1}{\text{mij}}, \frac{1}{\text{lij}}\right)$

Where i,j $= 1, \ldots\ldots$,n and i $\neq$ j

Table 8. Triangular Fuzzy Number (TFN) and AHP scale

Scale of AHP	Language-Related Factors	Scale of TEN	Opposite
1	Equally significant	(1,1,1)	(1,1,1)
2	Between equal and slightly more significant on the scale	(1,2,3)	$(\frac{1}{3}, \frac{1}{2}, 1)$
3	A little more significant	(2,3,4)	$(\frac{1}{4}, \frac{1}{3}, \frac{1}{2})$
4	Between slightly more significant and much more significant	(3,4,5)	$(\frac{1}{5}, \frac{1}{4}, \frac{1}{3})$
5	More important	(4,5,6)	$(\frac{1}{6}, \frac{1}{5}, \frac{1}{4})$
6	Between more important and actually more important is the scale.	(5,6,7)	$(\frac{1}{7}, \frac{1}{6}, \frac{1}{5})$
7	Really more important	(6,7,8)	$(\frac{1}{8}, \frac{1}{7}, \frac{1}{6})$
8	Between actually more important and definitely more important is the scale.	(7,8,9)	$(\frac{1}{9}, \frac{1}{8}, \frac{1}{7})$
9	Absolutely more important	(8,9,9)	$(\frac{1}{9}, \frac{1}{9}, \frac{1}{8})$

The final weights for applying the AHP and F-AHP criteria to determine the best locations for the plant in the research region are shown in Tables 9 and 10. As a result, the criteria's weights have been adjusted using ArcGIS software. The final digital map demonstrates the choice of three different ideal levels (high, moderate, and low suitability) for the plant in the study area, which appear in Figure 7.

Table 9. Pairwise comparison matrix AHP scale by Saaty

Criteria	SL	RN	LF	EG	RC	SW	AL	RL	E	TS
SL	1	1.2	1	2	2	3	4	4	5	11.2
RN	2	1	1.2	3.2	3.2	5.2	7.2	7.2	9.2	5
LF	1	2	1	1	1	2	3	3	4	9.2
EG	1.2	2.3	1	1	1	1	2	2	3	7.2
RC	1.2	2.3	1	1	1	1	2	2	3	7.2
SW	1.3	2.5	1.2	1	1	1	1	1	2	5.2
AL	1.4	2.7	1.3	1.2	1.2	1	1	1	1	3.2
RL	1.4	2.7	1.3	1.2	1.2	1	1	1	1	3.2
E	1.5	2.9	1.4	1.3	1.3	1.2	1	1	1	1
TS	2.11	1.5	2.9	2.7	2.7	2.5	2.3	2.3	1	1

SL=sensitive land; RN=road network; LF=landfills; EG=electricity grid; RC=River and channels; SW= surface water AL=agricultural land; RL=Railway Line; E=Elevation; TS=Terrain slope.

Table 10. Triangular Fuzzy Number (TFN) and AHP pairwise comparison matrix scale

Criteria	SL	RN	LF	LF	RC	SW	AL	RL	E	TS
SL	(1,1,1)	(1/3,1/2,1/1)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(3,4,5)	(3,4,5)	(4,5,6)	(9/2,11/2,13/2)
RN	(1,2,3)	(1,1,1)	(1/3,1/2,1/1)	(1,3/2,3)	(1,3/2,3)	(3/2,5/2,2/7)	(5/2,7/2,9/2)	(5/2,7/2,9/2)	(7/2,9/2,11/2)	(4,5,6)
LF	(1,1,1)	(1,2,3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)	(3,4,5)	(7/2,9/2,11/2)
EG	(1/3,1/2,1/1)	(1/3,3/2,1/1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(5/2,7/2,9/2)
RC	(1/3,1/2,1/1)	(1/3,3/2,1/1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(5/2,7/2,9/2)
SW	(1/4,1/3,1/2)	(2/7,2/5,2/3)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,2,3)	(3/2,5/2,2/7)
AL	(1/5,1/4,1/3)	(2/9,2/7,2/7)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(5/2,7/2,9/2)	(1,1,1)	(1,3/2,3)
RL	(1/5,1/4,1/3)	(2/9,2/7,2/7)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,3/2,3)
E	(1/6,1/5,1/4)	(2/11,2/9,2/7)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
TS	(2/13,2/11,2/9)	(1/6,1/5,1/4)	(2/11,2/9,2/7)	(2/9,2/7,2/7)	(2/9,2/7,2/7)	(2/7,2/5,2/3)	(1/3,2/3,1/1)	(1/3,2/3,1/1)	(1,1,1)	(1,1,1)

SL=sensitive land; RN=road network; LF=landfills; EG=electricity grid; RC=River and channels; SW= surface water AL=agricultural land; RL=Railway Line; E=Elevation; TS=Terrain slope.

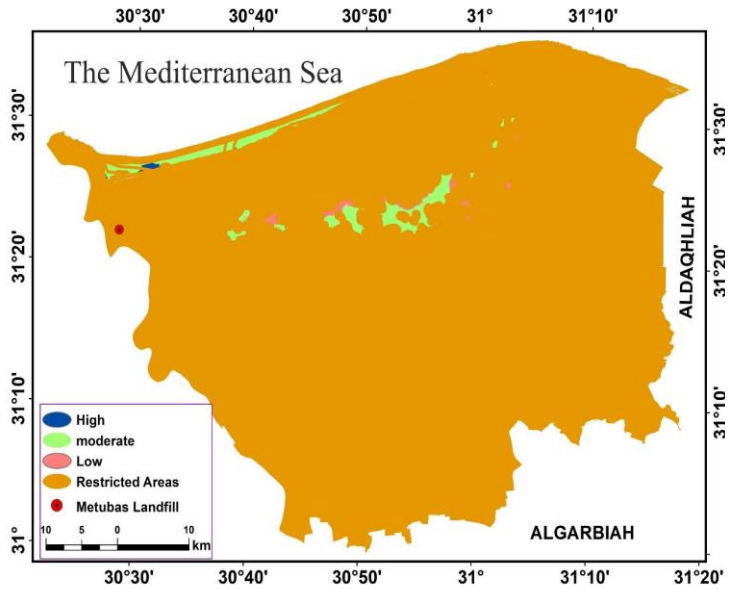

Figure 7. Integrated suitability map

4. Results and Discussion

4.1. Analysis of the Appropriateness of Each Criterion

Figures 4 and 8 show the outcomes of each criterion's classification (0–10) using ArcGIS 10.8 [33, 37]. The Kafrelsheikh Governorate has a widespread road system, which directly influences the economic viability of installing a station by lowering the cost of waste transportation. The percentage of the governorate's land area was 25% as a prohibited area for these criteria, 12% was very suitable, and the rest of the areas were of low to medium suitability. The Kafrelsheikh Governorate almost entirely has moderately to acceptable connectivity to the electrical grid. It has been noted that a sizable number of medium- to highly appropriate areas are restricted to agriculture, and the percentage prohibited for building according to the agricultural land standard was 89%. This indicates the large extent of the agricultural area in the governorate, but it is possible to build on this area in the event that unoccupied lands are not available. The height of the terrain in the Kafrelsheikh Governorate, which ranges from -28m to 133m (Figure 3-a), is seen to be particularly ideal for building a WTE plant. Most of the governorate's lands have slopes between medium and highly suitable, ranging from 0 to 66 degrees (Figure 3-b). 86% of the governorate's land was prohibited from being built on due to the sensitive land standard to avoid pollution resulting from those stations, and 7% was very appropriate. The prohibited area was 18% for surface water, 23% for rivers and canals, and 2% for railways, which indicates the small area of railways in the governorate. According to the criteria ranking, layers were created for each criterion according to this classification using ArcGIS 10.8.

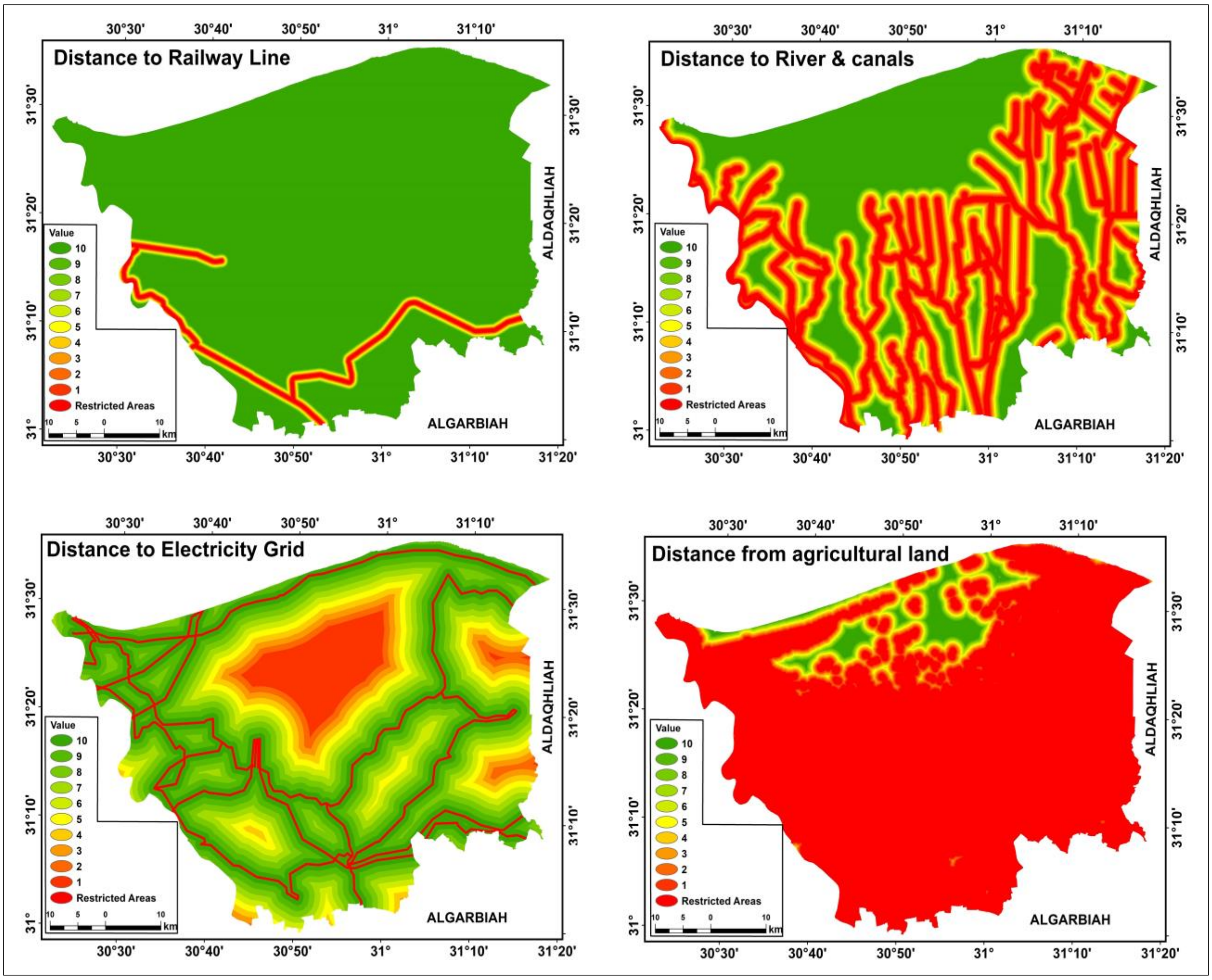

Figure 8. Displays the appropriateness rankings for each criterion in the following order: red (0) indicates a restricted region, 1-4 indicates low suitability, 5-7 indicates moderate suitability and 8–10 indicates high suitability

4.2. Analyses of Integrated Suitability

The appropriateness study of individual criteria does not offer a thorough evaluation and may be deceptive when numerous criteria yield contradicting conclusions. A weighted overlay in this case provides the opportunity to undertake an integrated suitability analysis and avoid inconsistent findings. After applying the weighted overlay tool using ArcGIS 10.8, the final map appears to have different appropriate categories within the Kafrelsheikh area. This investigation determined three categories: low, medium, and high suitability. According to Table 11, only 1.62% of the research area is suitable for a plant to be built; the remaining 96.76% cannot accommodate one. Only 0.04% of the land in the suitable zones falls into the highly suitable category that is highlighted with a blue color (Figure 7).

Table 11. The proposed criteria weights using AHP and Fuzzy AHP methods that have been applied

Criteria	Weights by AHP method	Weights by Fuzzy AHP method	Fuzzy AHP %
Distance to sensitive land uses	0.187	0.185	18.45
Distance to road network	0.179	0.182	18.25
Distance to landfills	0.164	0.156	15.65
Distance to electricity grid	0.109	0.109	10.86
River and main channels	0.109	0.109	10.86
Distance to surface water	0.076	0.075	7.55
Distance from agricultural land	0.052	0.054	5.44
Railway Line	0.052	0.055	5.45
Elevation	0.040	0.041	4.06
Terrain slope	0.033	0.034	3.43

According to the investigation, just one location has a suitable area with a total surface area of 1.3 km^2, while the remaining areas are all less than 100 m^2, which is not suitable to build a plant. Figure 7 shows this location at 30°33` N and 31°27` W, and at a distance of 1.8 km from the Metubas controlled landfill, which is a perfect distance to get rid of remaining residues. It receives an average of 1750 tons of waste per day, which is 67% of the total waste generated in Kafrelsheikh Governorate. Processes and their proximity to the road network reduce the cost of transporting waste. When evaluating the viability of the location for the facility, the wind direction must also be taken into account, given that the wind in the study area primarily blows from the northwest, according to the National Meteorological Agency reports. This will protect farming and populated areas from any potential annoyance effects from the new proposed plant, given that the specified site is located in the desert hinterland of the governorate.

This study adopted the standard method of using MCDM technology in ArcGIS 10.8 for decision-making. The ranks of each criterion were assigned by a questionnaire in which 34 people with experience in the research topic participated, which were used to calculate the relative weights in two different ways: AHP and fuzzy AHP (Table 11). In the paired comparison, the decisions' Consistency Ratio (CR) was also calculated. For consistency, CR metrics must equal or be less than 0.1 (10%) of the matrix, which is 0.01867 (1.867%). The results revealed little difference between the two applied methods and that keeping a safe distance between the facility and restricted or sensitive land was crucial and had the highest effect percentage (18.45%; Table 11). This aspect is crucial for choosing the location of the facility in order to preserve public health and avoid inconveniences like noise, emissions, and aromas.

Distance to the road network has the second-highest impact (18.25%), followed by the distance to landfills (15.65%) and the distance to the electricity network (10.86%) on the decision of where to locate the plant (Table 11). These factors directly affect the cost of operation and construction, accessibility to the site, and the supply of waste to the plant. Large amounts of solid waste must be transported to the site every day to enable the correct and effective operation of the plant. In order to ensure a continuous supply of waste at the station site, the accessibility of the waste source and the provision of infrastructure to connect the generated electricity to the national electrical grid are all essential.

The river and main canals (10.86%; Table 11) are equally important to the electricity grid due to the pollution caused by those stations. Relative weights of distance to surface water (7.55%), distance from agricultural lands (5.44%), and railway tracks (5.45%) reflect intermediate importance, while elevation (4.06%) and terrain slope (3.43%) have the most negligible impact on plant site selection (Table 11).

In a study conducted in the Lzmir metropolitan municipality [18], 97% of the study area was restricted and unsuitable for establishing the station. The criteria of proximity to transfer stations and MSW availability were the most important; elevation and slope were the least important, which indicates the importance of criteria related to the economy and their role in reducing operating costs. The station. In another study conducted in Pathumthani [17], the criteria of distance from urban areas, distance from main water resources, and distance from power stations were the most important; railways and airports were the least important. Other Abushammala et al. [16] found that distance to sensitive land uses and distance to landfills had the highest weight, while terrain slope and distance to the airport had the least weight. The standards and their importance differ from one region to another according to the nature of the study area. After reviewing previous literature, the economic and environmental criteria had the highest value, and this confirms the importance of operating the station. At the lowest cost while preserving the surrounding environment due to the pollution these buildings cause.

5. Conclusions

- For the sake of sustainable development, Kafrelsheikh Governorate must establish a station to convert solid waste into energy to address the problem of the increasing amounts of solid waste generated due to the expected population increase and the increase in electricity supplies. To choose the appropriate location for these buildings, many standards and classifications are required because a wrong choice would be harmful to the environment, natural resources, and health. Human resources and increases construction and operating costs.
- The study proposes the use of AHP and fuzzy AHP models, which were developed by integrating them with MCDM methods and a GIS, to determine the location of a waste-to-energy station in Kafrelsheikh Governorate. It has proven to be one of the best techniques and a powerful tool for selecting sites.
- Due to its ample space and proximity to the controlled landfill Metubas in the Kafrelsheikh Governorate of Egypt, the integrated suitability analysis only identified one site as appropriate for constructing a WTE facility. In contrast, the total area of the governorate is 3738.48 km^2; only 60 km^2 of the governorate land was suitable for establishing a power plant from waste, and only 1.3 km^2 is the best suitable.
- The current study can apply its methodology and use its findings in many other fields of study to help decision-makers choose suitable buildings for many buildings, not just for waste-to-energy plants. In conclusion, the integration of MCDM and GIS is a powerful and promising tool in the field of solid waste management.

6. Nomenclature

GIS	Geographic Information Systems	DEM	Digital Elevation Model
MCDM	Multi Criterion Decision Making	AD	Anaerobic Digestion
AHP	Analytical Hierarchical Process	UTM	Universal Transverse Mercator
SW	Solid Waste	DEM	Digital Elevation Model
SWM	Solid Waste Management	USGS	United States Geological Survey
SVM	Support Vector Machine	CR	Consistency Ratio
WTE	Waste To Energy	CI	Consistency Index
TFN	Triangular Fuzzy Number	RI	Random Index
GOPP	General Organization for Physical Planning	WA	Weighted Average
CO_2	Carbon dioxide	W	Weighted vector
DANP	Decision-making and trial evaluation laboratory-analytical network process		

7. Declarations

7.1. Author Contributions

Conceptualization, A.B. and M.H.F.; methodology, A.S.; software, W.M.; validation, A.B., M.H.F., and A.S.; formal analysis, A.S.; investigation, A.B.; resources, M.H.F.; data curation, W.M.; writing—original draft preparation, A.S.; writing—review and editing, A.B.; visualization, A.S.; supervision, M.H.F.; project administration, A.B.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

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