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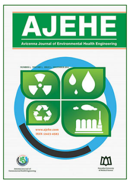

Original Article

Prioritization of Sanitary Landfill Criteria Using a Modified Delphi Approach and Development of a Tool for Efficient Site Selection

Farshad Bahrami Asl[1]*, Seyed Elyas Amini Rabati[2], Mohammad Taghi Samadi[3], Saeed Hosseinpoor[1], Yousef Poureshgh[4], Elnaz Alipour[1], Anahita Dehghani[1]

[1]Department of Environmental Health Engineering, School of Public Health, Urmia University of Medical Sciences, Urmia, Iran
[2]Student Research Committee, Urmia University of Medical Sciences, Urmia, Iran
[3]Research Center for Health Sciences and Department of Environmental Health Engineering, School of Public Health, Hamadan University of Medical Sciences, Hamadan, Iran
[4]Department of Environmental Health Engineering, School of Health, Ardabil University of Medical Sciences, Ardabil, Iran

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***Corresponding author:**
Farshad Bahrami Asl,
Email: Farshadfba@gmail.com

Abstract

Selecting a suitable and sustainable site for landfilling is a complex and multidimensional problem that involves various environmental, social, economic, and technical factors. Several approaches exist for selecting an appropriate sanitary landfill, each with its own challenges. This study addresses the need for a systematic and expert-driven prioritization of landfill site selection criteria. In this study, due to its ease, affordability, and primarily its capacity to assess numerous criteria simultaneously, a modified Delphi approach was employed to systematically prioritize the criteria for sanitary landfill site selection. The study followed a three-round Delphi design with 15 experts from relevant fields. Using a 10-point scale, experts rated 31 criteria derived from the literature that influence landfill siting decisions. The criteria spanned various landfill aspects and were categorized into three importance levels based on their weights, which was assigned by the experts using a 5-point scale. According to the results of the Delphi method, the most significant criteria for selecting landfill sites were groundwater quality, proximity to sanitary water source protection zones, hydrogeological features, and geotectonic characteristics, with respective weighted scores of 45.12, 41.76, 39.84, and 37.44 (weight = 4.80). The first-level criteria reflect the possible influence of landfill leachate on the quality and quantity of water resources and the welfare and contentment of nearby communities. This study also proposed a tool to calculate the final score of the potential landfill sites based on the weighted scores of the sub-levels of the criteria. The final score serves as a measure of the overall suitability and sustainability of each site, with a higher score indicating greater desirability when comparing various locations.

Keywords: Criteria prioritization, Delphi method, Landfill site selection, Solid waste

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1. Introduction

The management of solid waste poses various political, socioeconomic, institutional, and environmental challenges. It adversely affects the development of urban areas in developing countries, particularly those with low income (1). The urban environment and human health are adversely affected by the inadequate management of solid waste, which in turn impairs productivity and economic growth (2). This issue stems from poor urban policies and regulations and neglect of private and community participation in urban development and management (2).

The growing amount of waste and its environmental impact have changed the waste disposal concept in urban planning. Modern waste disposal strategies aim to be more sustainable and eco-friendlier, by reducing waste generation, increasing the use of recycled and reusable materials, and enforcing strict rules for proper waste handling (3). Landfilling is one of the most appropriate principles of waste management for residuals that cannot be reused, recycled, or recovered (4). The landfill is a common and cost-effective disposal method, accounting for 70% of waste disposal (5). Sanitary landfills are facilities where municipal solid waste (MSW) is disposed of in a controlled manner. They are designed and operated according to strict regulations and standards to protect human health and the environment from potential contaminants, such as leachate and landfill gas (4). However, the selection of suitable sites is a major challenge in landfilling (6-9).

Site selection affects not only urban solid waste landfills but also hazardous waste and recycling facilities (10, 11). Choosing a proper site for a landfill ensures that the waste disposal is effective and sanitary and complies with regulatory and environmental standards (6, 12). An inappropriate site can have negative impacts on important environmental aspects, such as natural habitats, water and soil quality, soil fertility, and landscape (13). Therefore, one of the most critical steps in landfill planning is identifying and finding a suitable location for the landfill. This process is complicated and entails the consideration of diverse criteria, such as environmental, financial, social, and technical aspects, each carrying a particular significance and imposing certain constraints on the selection (6, 8, 14). This step is essential for sustainable waste management and urban development (15).

A considerable effort has been made to address the issues surrounding the location of the sanitary waste landfill and the methodology used to determine its location. The suitability of landfill sites in Kolkata, India, was analyzed by Ali and Ahmad (16) using fuzzy analytical hierarchy process (AHP) and GIS. They used a 1-5 scale to rate the criteria for landfill suitability. They used a weighted linear combination (WLC) of the criteria to model the candidate sites. Using GIS, fuzzy logic, AHP, and WLC, Zarin et al (17) selected suitable landfill sites in Islamabad, Pakistan, based on 13 criteria grouped into environmental and socioeconomic categories. The criteria were weighted by AHP and standardized by fuzzy set theory. The Delphi method is a systematic approach or method in research to extract opinions from a group of experts on a topic or question. In other words, the Delphi method is a request for professional judgments from heterogeneous and independent experts on a specific topic at a large geographic level using a series of questionnaire rounds until reaching a group consensus while maintaining the anonymity of the respondents and feedback to the panel members. The Delphi method can be used for predicting the future, making decisions, and increasing its effectiveness, judging, facilitating problem-solving, assessing needs, setting goals, helping to plan, setting priorities, organizing group communications, group information gathering, determining policies, allocating resources, and group consensus or agreement.

While various multi-criteria decision-making methods, such as the AHP, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and GIS-based approaches, have been extensively applied for landfill site selection and criterion weighting (18-24), these methods often rely on predefined criteria sets or can be susceptible to biases inherent in direct group discussions. The unique challenge in landfill siting is the need to integrate diverse expert knowledge across environmental, social, and economic domains to form a robust consensus-driven set of priorities. This study proposes a novel application of a modified Delphi approach to systematically prioritize a comprehensive set of sanitary landfill criteria. The innovation of this research lies in leveraging the iterative, anonymous expert feedback mechanism of the Delphi method to minimize bias and achieve a robust consensus on critical site selection factors, a distinct advantage over single-round surveys or direct group interaction methods. Furthermore, this research develops a practical tool based on these expert-derived priorities, offering a systematic and efficient way to evaluate potential landfill sites. This approach not only ensures a more reliable and context-specific prioritization of criteria but also addresses the inherent subjectivity in expert judgment through a structured consensus-building process. The most important conditions required for the application of Delphi are the need for experts' judgment and opinions of a broad group, group agreement on achieving results, the existence of complex, large, and interdisciplinary problems and lack of agreement or insufficient knowledge, availability of experienced specialists, geographical dispersion, the need for anonymity in data collection, no time limit, and lack of another cost-effective method (25). This study aims to collect and prepare a list of all effective criteria in selecting the appropriate location of sanitary landfills, modifying, finalizing, and prioritizing them using the Delphi method so that finally an index can be presented according to the majority of effective criteria in selecting the location of sanitary landfills to select the suitable location for these landfills.

2. Materials and Methods

This study followed a three-round Delphi design. The Delphi method involves a sequence of surveys that are designed to facilitate agreement among a panel of specialists on a certain issue. It has been employed in domains such as forecasting, decision-making, problem-solving, and consensus formation (26-30). The main steps of the Delphi method are: (a) selecting the experts, (b) designing and distributing the questionnaire, (c) analyzing and summarizing the responses, (d) modifying and redistributing the questionnaire, and (e) repeating the process until a convergence of opinions is achieved (26).

2.1. Participants

A team of researchers was formed to implement and monitor the Delphi process. While there is no universally fixed number for Delphi panels, a panel of 10-15 experts is commonly recommended, even for heterogeneous groups, to ensure sufficient statistical power and diverse perspectives while maintaining manageability. Our primary recruitment criterion was the proven expertise and extensive practical and academic experience in fields directly related to landfill site selection and solid waste management. To minimize selection bias and ensure comprehensive coverage of the multifaceted aspects of landfill siting (environmental, geological, hydrological, social, economic, and engineering), the team selected a multidisciplinary panel of 15 experts from relevant academic or professional backgrounds, including environmental engineering, waste management, urban planning, and hydrogeology. The experts also had sufficient knowledge and experience in landfill site selection and were familiar with the literature on the topic. The inclusion criteria for selecting the experts were as follows: (a) having at least a master's degree or equivalent qualification in a related field, (b) having at least five years of work experience in a related field, (c) having published at least one paper or report on landfill site selection or related topics, and (d) being willing to participate in all three rounds of the questionnaire. The experts were asked to participate in all three rounds of the questionnaire and were assured of anonymity and confidentiality.

2.2. Questionnaire

The main material used in this study was a questionnaire that consisted of 31 questions. The questions were derived from a comprehensive literature review on landfill site selection criteria (14, 31-33). The questions covered various aspects of landfill site selection (Table 1). The criteria were grouped into three levels: first level (general and important criteria), second level (a subset of first level criteria), and third level (a subset of second level criteria). The questionnaire was designed using a scale ranging from 1 (less important) to 10 (very important). The experts were asked to rate each criterion according to their level of agreement or importance. They were also encouraged to provide comments or suggestions for improving or modifying the questions.

The selection of a 1-10 Likert scale for expert ratings was a deliberate choice based on its advantages for our Delphi methodology. This scale offered an optimal balance between sufficient granularity and cognitive ease for experts, ensuring consistent and thoughtful responses. Its intuitive understanding and ample discriminatory power allowed for clear distinction between varying degrees of importance without forcing artificial precision. This facilitated the iterative consensus-building process essential for robust criteria prioritization. While a formal

Table 1. Studied Criteria, their Weights, and Averaged and Weighted Scores after Three Rounds of the Delphi Survey to Select a Suitable Landfill Site

	Criteria	Averaged score[1]	Weighted score[2]
Level 1 (weight = 4.8)	• Groundwater	9.4	45.12
	• Distance from protected water resources	8.7	41.76
	• Hydrogeological characteristics	8.3	39.84
	• Geotectonic features	7.8	37.44
	• Available area for disposal of waste and associated activities	7.4	35.52
	• Average precipitations	7.1	34.08
	• Distance from nearby developed or urban residential areas	6.9	33.12
	• Topographical features	6.8	32.64
	• General acceptability of the site	6.3	30.24
Level 2 (weight = 3.6)	• Distance from drinking water supply wells	8.3	29.88
	• Distance from surface waterways	8.2	29.52
	• Engineering-geological properties	7.7	27.72
	• Earthquake activity	7.1	25.56
	• Distance between cover soil and the site	6.8	24.48
	• The current infrastructure of the site	6.7	24.12
	• The proximity of the landfill to the waste collection area	6.6	23.76
	• Present utilization of land	6.5	23.4
	• Landscape features	6.4	23.04
	• Activities required for land preparation	6.2	22.32
	• Distance to sacral, cultural, or protected natural landmarks	5.8	20.88
	• Distance from railways and roads	5.6	20.16
Level 3 (weight = 2.5)	• Potential for phased construction and expansion	6.4	16
	• Annual average of wind intensity and direction	6	15
	• Distance to domiciles located outside of established communities	5.9	14.75
	• Land ownership	5.8	14.5
	• Distance from drinking water pipeline, gas pipeline, crude oil pipeline, and main transmission line	5.3	13.25
	• Distance to land dedicated to agriculture	5.2	13
	• Access road (road reconstruction, new road construction)	5.1	12.75
	• The visibility of the site from far distances	4.7	11.75
	• Annual average of air temperature	4.4	11
	• The distance to the nearest power supply location	3.6	9

[1] Rounded average

[2] Average*weight

The table is based on highlighted numbers and the colors are provided here for visual comparison sensitivity analysis comparing the 1-10 scale to other scales was not performed due to practical constraints, the robustness of our results was ensured by several methodological aspects. The iterative Delphi rounds and predefined consensus thresholds validated the ability of the scale to capture meaningful distinctions. Furthermore, the detailed calculation of sub-level scores provided the necessary granularity for practical application, ensuring that the final prioritized list and derived tool reliably could reflect expert judgment. The questionnaire was validated by a group of experts in the relevant fields before being distributed to the panel. The reliability was assessed using the test-retest method with a sample of 10 experts who completed the questionnaire twice at a two-week interval. The reliability was measured by calculating Pearson's correlation coefficient between the two sets of data. A high correlation coefficient indicated that the questionnaire was reliable.

2.3. Procedure

The research team conducted three rounds of Delphi using email as the communication medium. In each round, the questionnaire was sent to the experts, and they were given a specified time frame to complete and return it. After each round, the researchers analyzed the data and prepared a summary report that showed the descriptive statistics, comments, and feedback from the previous round. The summary report was then sent to the experts along with the next round of questionnaires. The experts were encouraged to revise their ratings considering the summary report, if needed, or maintain their original ratings with justification. The process was terminated after three rounds when a satisfactory level of consensus was achieved, and no significant changes were needed and observed in the ratings. We used the coefficient of variation (CV) to assess the degree of consensus among experts. A lower CV indicated a higher degree of consensus. We established a pre-defined threshold for the CV ($CV < 15\%$) to define when consensus was reached for a given criterion. Experts were also asked to assign numerical weights, ranging from 1 to 5, to each of the three levels of the criteria to indicate their relative importance. The criteria were organized hierarchically; in other words, the first level was more significant than the second, and the second was more significant than the third.

2.4. Data Analysis

The data collected from the expert questionnaires were analyzed using SPSS version 16.0. For each Delphi round, descriptive statistics were calculated, including means, standard deviations, and CVs for the expert ratings of each criterion. The CV was specifically used to assess the convergence of expert opinions, with a predefined threshold ($CV < 15\%$) indicating consensus. Criteria that did not reach consensus after a round were re-evaluated in subsequent rounds. The final round of the Delphi process resulted in a prioritized list of criteria for landfill site selection. Each criterion studied had 5 sub-levels. Following the calculation of the total score of each criterion, we distributed it among its sub-levels using a unique methodology. This method ensured that the sub-level scores directly reflected the overall hierarchical importance established by the experts. Specifically, after all main criteria were ranked based on their final weighted scores, the numerical difference between any two consecutively ranked criteria was calculated. This difference was then evenly divided by the 5 sub-levels to yield an incremental value. Starting from the weighted score of the higher-ranked criterion, this incremental value was successively subtracted to determine the scores for its corresponding 5 sub-levels. This granular and consistent scoring system was crucial for evaluating different quality or condition levels within each criterion, directly linking it to the overall expert-derived importance. Tables 2 to 4 show the scores of all sub-levels of the studied criteria at three different levels. The results of the Delphi study were analyzed using Excel software and the final score of the proposed landfill was calculated using equation 1.

$$TSL = \sum Wi \times Si \qquad (1)$$

Where TSL is the total score of landfills, Wi is the weight of i level, and Si is the total score of i level.

3. Results and Discussion

According to the study design and the obtained results, the first-level criteria had the highest weight (4.8), the second-level criteria had a moderate weight (3.6), and the third-level criteria had the lowest weight (2.5). Table 1 summarizes the results of the Delphi method, showing the weight, average score, and weighted score for each criterion. Groundwater is widely recognized as one of the most critical criteria for selecting a landfill site, as it reflects the potential impact of leachate leakage on the quality of groundwater resources, which are essential for human and ecological use (14, 34-40). Groundwater pollution from landfill leachate poses a persistent and serious risk to human health and environmental quality. To mitigate this risk, a buffer zone must be established between the groundwater table and the produced leachate, as recommended by previous studies (14, 37, 41). Additionally, monitoring wells must be installed both downstream and upstream of the landfill site to detect any anomalies and incidents (14).

In our study, groundwater was ranked as the most important criterion with an average score of 9.4 and a weighted score of 45.12 (Tables 1 and 2), which is in agreement with previous studies (38, 39, 40, 42, 43). Other studies ranked groundwater as the second most important factor (13), however it was less influential than the population factor, and the third most important factor (9), less influential than the surface water and aquifer type, but still gave it a high weight or score.

Among the other criteria in the present study, the

Table 2. First Level Criteria with their Scores

Criteria	**Score**
Groundwater	
Aquifer is non-existent.	45.12
The water level of the aquifer is more than 3 m below the floor of the landfill.	44.45
The water level of the aquifer is 1 to 3 m below the floor of the landfill.	43.78
Water level of the aquifer rarely exceeds bottom of the landfill and its wetting is possible.	43.10
The groundwater level is higher than the landfill floor permanently or temporarily.	42.43
Distance from protected water resources ((a) protection zone with a smaller width; (b) protection zone with a larger width)	
>1500 m (a);>2000 m (b)	41.76
1000-1500 m (a); 1000-2000 m (b)	41.38
500-1000 m	40.99
200-500 m (a); up to 500 m (b)	40.61
0-200 m	40.22
Hydrogeological characteristics	
Clay and flysch materials with a hydraulic conductivity (k) less than or equal to 10^{-9}m/s and a layer thickness equal to or greater than 1 m exhibit impermeability to water.	39.84
Materials possessing low water permeability include impermeable complexes of $10^{-6} \geq k \geq 10^{-9}$ m/s and those with thin layer thicknesses, not exceeding 1 m.	39.36
Low-porosity rocks such as alluvial and glacial sediments	38.88
Intergranular-porosity rocks such as coarse-grained gravel	38.40
Fissure-cavernous porosity rocks such as karstified rocks, limestones, and dolostones with great permeability of water	37.92
Geotectonic features	
Rocks formed by cooling and solidification of magma	37.44
Materials carried and deposited by glaciers	37.06
Layers of rocks formed by erosion and deposition of clay, lime, sand, etc.	36.67
Rocks made of minerals that react with acid and have many caves and sinkholes above and below ground or level land	36.29
The fault zone	35.90
Available area for disposal of waste and associated activities	
Adequate area for more than 20 years	35.52
Adequate area for 20 years	35.23
Adequate area for 15 years	34.94
Adequate area for 10 years	34.66
Adequate area for 5 years	34.37
Average precipitations	
<300 mm	34.08
300-600 mm	33.89
600-1000 mm	33.70
1000-1500 mm	33.50
>1500 mm	33.31
Distance from nearby developed or urban residential areas	
More than 5000 m and more than 2500 m for site without and with shelter, respectively	33.12
up to 5000 m and 2000-2500 m for site without and with shelter, respectively	33.02
up to 4000 m and 1500-2000 m for site without and with shelter, respectively	32.93
2000-3000 m and 1-1500 m for site without and with shelter, respectively	32.83
1500-2000 m and 750-1000 m for site without and with shelter, respectively	32.74
Topographical features	
A gentle slope or level ground that inherently is suitable for landfill siting or need small preparation of the previously artificially constructed hollows or mounds	32.64
A compacted construction and mining wastes that have naturally suitable slope or hollows for landfill siting	32.16
An incompact spatial entity encompasses multiple valleys and features innately configure terrain that are conducive to the formation of said valleys.	31.68
A fractured topography, undulating terrain, and a condensed spatial morphology	31.20
The incompact spatial entity comprising multiple valleys exhibits broken relief and highly uneven terrain, notably prominent in karst landscapes.	30.72
General acceptability of the site	
There is public consent.	30.24
There is public consent along with moderate local dissent.	30.17
There is public consent along with some local officials' dissent.	30.10
There is public consent along with complete local dissent.	30.02
There is no public consent.	29.95

distance from protected areas of sanitary water supply sources holds paramount importance, adhering to stringent guidelines and standards. This criterion received a weighted score of 41.76, indicating its high relevance for landfill site selection. However, this criterion was not explicitly addressed in most previous studies under this name. Nevertheless, groundwater and surface water, which were commonly used as criteria in other studies, can also be regarded as sources of drinking water. Hence, the literature review reveals the significance of distance from drinking water for landfill site selection (28, 34, 35). For example, Ghaed Rahmat et al (39) ranked groundwater and surface water as the top two criteria among 10. Pasalari et al (40) gave more weight to environmental than socio-economic criteria, and within the environmental ones, groundwater, surface water, and distance to wells had the highest weights. Compared to these studies, the distance from the wells and surface water in our study, with weighted scores of 29.88 and 29.52 respectively, were assigned a lower level of importance. The possible reasons for the discrepancy could result from using greater criteria in this research, which is more than most other studies, and also from the diverse perspectives of the experts involved.

The hydrogeological attributes of the site were the third most important criterion, with a weighted score of 39.84. This criterion assesses how the geological and hydrological features of the site, such as soil type, permeability, porosity, and hydraulic conductivity, influence the generation, movement, and natural degradation of leachate. Therefore, the site should have favorable hydrogeological conditions that minimize leachate production and facilitate its natural attenuation. Previous studies have also highlighted the importance of hydrogeology for landfill site selection (28, 32, 37). For example, Gorsevski et al (37) assigned the highest rank of importance to this criterion. Leachates may leak out of geologic faults and cause environmental damage by flowing preferentially along the fault lines (44). Reflecting its significance, the criterion of geotectonic features was a first-level criterion according to the experts in our study (Tables 1 and 2), which agrees with the study conducted by Donevska et al (20).

Our findings indicate that the proximity of the landfill to populated areas is a moderately significant criterion in level one, with a weighted score of 33.12. This criterion is also commonly used and valued in several previous studies that evaluate the environmental and social impacts of landfill siting (13, 19, 32, 40). Studies have recognized the potential effects of noise, odor, dust, traffic, or visual degradation on the nearby communities, which may impair their well-being and property values and cause social conflicts and opposition (22, 39). Therefore, they recommend selecting a site that is sufficiently distant from residential areas and implementing measures to mitigate or prevent the negative consequences of landfill operation. However, the relative importance of this criterion varies across different studies, depending on the context and methodology adopted. For instance, Khorsandi et al (42) prioritized this criterion after the factors related to water resources protection. Ghaed Rahmat et al (39) ranked this criterion as the fourth most important one, after ground and surface waters, and sensitive ecosystems. In contrast, Pasalari et al (40) considered residential areas at the top of the socio-economic criteria list. Kapilan and Elangovan (13) assigned the highest weight to the population factor, compared to other factors such as depth to the water table and land use/landcover.

The second-level criteria comprise 12 factors that reflect various aspects of landfill siting, such as the geotechnical properties, terrain preparation, landscape features, infrastructure, and so on (Tables 1 and 3). Some of these factors, such as land use, distance to waste production/generation centers, distance to faults/seismic risk, and distance to archaeological sites/cultural areas, have been widely used by other researchers for landfill siting, as shown by Donevska et al (32), who reviewed 89 papers on this topic. However, infrastructure, which is a moderately important factor in our study, was found to be less significant in some other studies (38, 40). Among the third-level criteria (Tables 1 and 4), some of the least influential criteria were the temperature, access road, and airstream, with average scores of 4.40, 5.10, and 6.00, respectively, and weighted scores of 11.00, 12.75, and 15.00, respectively. Our results are in line with some previous studies that have also considered these criteria as relevant but not decisive for landfill siting. For example, Rahimi et al (21) included average annual temperature as a factor affecting construction operations, disease spreading, and contamination rate, but it was ranked higher than the distance from urban and rural areas and had more priority compared to our study. Aksoy and San (18) studied 12 criteria including temperature, which had the lowest weight in their list, consistent with our results. Fallahpour et al (38) included the secondary road with the lowest weight as a factor affecting accessibility. Pasalari et al (40) included the access road and wind direction as sub-criteria of socio-economic criteria to select the optimal location for a landfill.

The findings of our study carry significant practical implications for the sustainable management of MSW, particularly concerning the critical process of landfill site selection. The systematically prioritized criteria, derived from a robust modified Delphi approach involving expert consensus, provide a valuable framework for decision-makers, environmental agencies, urban planners, and local authorities. First, the hierarchical importance assigned to criteria (e.g., the high priority of groundwater quality and hydrogeological characteristics) offers clear guidance, enabling policymakers to focus resources and regulatory efforts on the most critical environmental and public health safeguards during the planning phase. This reduces the subjectivity often associated with such complex decisions and promotes a more objective evidence-

Table 3. Second Level Criteria with their Scores

Criteria	**Score**
Distance from drinking water supply wells	
• More than 200 m and 1500 m for wells located upstream and downstream of the landfill, respectively	29.88
• Up to 200 m and 1000-1500 m for wells located upstream and downstream of the landfill, respectively	29.81
• 500-1000 m downstream or at the landfill level	29.74
• Within 500 m downstream or at the landfill level	29.66
• 100-200 m, either at landfill level or downstream of it	29.59
Distance from surface waterways	
• The absence of waterways nearby, minimal susceptibility to flooding, limited precipitation inflow, and ease of safeguarding against water-related hazards are notable characteristics	29.52
• Permanent waterways at more than 1 km pose no flooding risk; standard solutions can be employed to defend the site.	29.16
• The substantial influx of rainwater from proximate catchment areas necessitates more sophisticated infrastructure for safeguarding against these waters, with no flooding risk.	28.80
• Minor waterways, such as brooks and torrents, the potential for flooding exists and the requirement for displacement or channelization of the flow of water is paramount.	28.44
• Within 500 to 1000 m, there are permanent rivers or standing bodies of water, with a potential vulnerability to floods during periods of elevated water levels. Implementation of protective protocols against high waters is necessary.	28.08
Engineering-geological properties	
• Solid rock formations and stable slopes, even those with steep inclines	27.72
• The rocks exhibit coherence, a slight degree of lithologic alteration, and stability within slopes.	27.29
The rocks seem semi-coherent, which is facing the possibility of landslides during ponderous falls.	26.86
• The possible occurrence of landslides due to the undercutting of slope foot in a complex of semi-coherent and incoherent rocks (diluvial sediments)	26.42
• Rocks without cohesion, unstable gradients, falling or sliding movements, and ongoing landslides	25.99
Earthquake activity	
• <5 MCS	25.56
• 5 MCS	25.34
• 6 MCS	25.13
• 7 MCS	24.91
• 8 MCS to 9 MCS	24.70
Distance between cover soil and the site	
Onsite	24.48
up to 1000 m	24.41
1000-2000 m	24.34
2000-5000 m	24.26
>5000 m	24.19
The current infrastructure of the site (access road, electricity, water supply line, etc.)	
The majority, if not all, of the various infrastructure exist.	24.12
Infrastructure exist moderately.	24.05
Infrastructure exists weakly.	23.98
Infrastructure exist Inadequately.	23.90
No infrastructure exists.	23.83
The proximity of the landfill to the waste collection area	
It is situated close to the municipalities with the highest quantities of municipal solid waste, within a 10 km radius from the central point of the region.	23.76
Relative to the region, it is centrally located.	23.69
It is located within a 10 km radius of the central point of the region.	23.62
It is located within a 20 km radius of the central point of the region.	23.54
It is located at the periphery of the region, completely displaced from its central position.	23.47
Present utilization of land	
Infertile land, dense vegetation, unproductive land, mining sites, and quarries	23.40
Grazing fields, woodland shrubs	23.33

Table 3. Continued.

Criteria	Score
Grasslands	23.26
High-quality forests	23.18
Farming land used for plowing or orchards, residences like individual houses within properties, and sports grounds	23.11
Landscape features	
There will be no disturbance to the environment, neither during operation nor after landfill closure.	23.04
Landfill operation slightly disturbs the natural environment but restores it to an undisturbed state after closure.	22.90
There will be disturbance to the natural environment, both during the operation of the landfill and to a less degree after closure.	22.75
There will be significant disturbance to the natural environment, both during the operation of the landfill and, to some extent, following landfill closure.	22.61
There will be significant disturbance and transformation of the natural environment during landfill operations, as well as post-closure.	22.46
Activities required for land preparation	
Simple operations will be needed without using the machines.	22.32
Machines will be used to level the terrain on the smaller section of the site.	22.03
Terrain leveling on most of the site will be completed using machines.	21.74
Only certain areas of the site will require blasting for complex terrain leveling.	21.46
The most challenging type of terrain preparation will be extensive blasting to level most of the site.	21.17
Distance to sacral, cultural, or protected natural landmarks	
>2500 m, or>1500 m with shield	20.88
2000-2500 m, or 1250-1500 m with shield	20.74
1500-2000 m, or 1000-1250 m with shield	20.59
1250-1500 m, or 750-1000 m with shield	20.45
1000-1250 m, or 500-750 m with shield	20.30
Distance from railways and roads (major roads (with shield/without shield), and minor roads (with shield/without shield))	
>600 m |>1000 m,>400 m |>600 m	20.16
600 m | 1000 m, 400 m | 600 m	19.33
>500 m |>800 m,>300 m |>500 m	18.50
>400 m |>600 m,>250 m |>400 m	17.66
>300 m |>500 m,>200 m |>300 m	16.83

based approach. Second, by providing a transparent and replicable methodology for criteria prioritization, this research empowers local authorities and stakeholders to engage in more informed discussions regarding landfill development. It facilitates a common understanding of the critical factors, which can lead to greater public acceptance and more effective implementation of waste management strategies. Ultimately, the results of this study directly contribute to building more sustainable waste infrastructure by guiding the selection of sites that mitigate risks, protect natural resources, and align with long-term environmental protection goals.

3.1. Challenges and Solutions

The Delphi method, despite its advantages, faced some challenges and limitations that could affect the validity and reliability of the findings. These challenges included the difficulty of finding and retaining qualified and willing experts, the subjectivity and bias of some experts, the complexity and ambiguity of some criteria, and the lack of sufficient literature or data on some criteria. To address these issues, the researchers adopted several strategies, such as conducting a thorough search for potential experts, sending reminders and follow-up messages to the experts, and ensuring the anonymity of participants (30). We also provided clear instructions and definitions for each criterion and question, used multiple rounds of questionnaires, and verified and cross-validated the findings with other studies or methods. These strategies improved the validity and applicability of the criteria and the consensus among the experts. Additionally, the authors assessed the reliability of the questionnaire by correlating the responses of 10 experts who completed it twice with a two-week interval, and the high correlation indicated high reliability.

4. Conclusion

This study used a modified Delphi method, a reliable technique for gathering and synthesizing expert opinions, to identify and prioritize the criteria for choosing a suitable and sustainable landfill site. The study involved 15 experts who rated 31 criteria on a 10-point scale in three rounds of questionnaires. The criteria were grouped into three levels of importance, based on their weight and role in ensuring the feasibility and performance of the landfill site. The results revealed that the most important criteria for landfill

Table 4. Third Level Criteria With Their Scores

Criteria	Score
Potential for phased construction and expansion	
The potential for phased construction and expansion is unlimited.	16.00
The potential for phased construction and expansion is limited.	15.80
The potential for phased construction exists; however, expansion is not feasible.	15.60
The potential for phased construction is limited; however, expansion is not a feasible option.	15.40
There is no potential for phased construction and expansion in future.	15.20
Annual average of wind intensity and direction	
The prevailing winds typically blow in the opposite direction, emanating from inhabited areas and other locations where individuals reside and labor.	15.00
The prevailing winds blow in the opposite direction, emanating from inhabited areas and other locations where individuals reside and labor, while weaker winds blow towards where individuals reside and labor.	14.95
The directions of prevailing winds towards the relevant facilities are variable.	14.90
Frequent weaker winds are oriented towards pertinent facilities with a prevailing wind direction.	14.85
Strong winds with high frequency and dominant direction mainly blow towards residential areas.	14.80
Distance to domiciles located outside of established communities	
>1500 m	14.75
1500 m	14.70
1000 m	14.65
500 m	14.60
<250 m	14.55
Land ownership	
All of the selected land is fully owned by the government.	14.50
Approximately half of the selected land is privately owned, and the other half is owned by the government.	14.25
Approximately 75% of the selected land is privately owned, while around 25% is owned by the government.	14.00
Private ownership encompasses 100% of the selected land and this land has few owners.	13.75
Private ownership encompasses 100% of the selected land and this land has many owners.	13.50
Distance from drinking water pipeline, gas pipeline, crude oil pipeline, and main transmission line	
500 m	13.25
300-500 m	13.20
200-300 m	13.15
100-200 m	13.10
up to 100 m	13.05
Distance to land dedicated to agriculture	
>1000 m	13.00
500-1000 m	12.95
300-500 m	12.90
100-300 m	12.85
<100 m	12.80
Access road that should be constructed (road reconstruction, new road construction).	
A suitable and acceptable access road is available.	12.75
<300 m,<200 m	12.55
300-800 m, 200-500 m	12.35
800-1500 m, 500-1000 m	12.15
>1500 m, 1000 m	11.95
The visibility of the site from far distances	
Not readily apparent, unless in close proximity	11.75
A distant view provides a glimpse of the locality surroundings	11.60
Many areas of the site are shielded and imperceptible.	11.45
Only limited few areas are safeguarded and out of sight.	11.30
The site remains visible from all vantage points and distances.	11.15
Annual average of air temperature	
>15 °C	11.00
12-15 °C	10.60
9-12 °C	10.20
6-9 °C	9.80
<6 °C	9.40
The distance to the nearest power supply location	
<300 m	9.00
300-500 m	7.20
500-1000 m	5.40
1000-2000 m	3.60
>2000 m	1.80

site selection were groundwater, distance from protected areas of sanitary water supply sources, hydrogeological attributes of the site, and geotectonic features. These criteria reflect the potential impacts of landfill leachate on the quality and quantity of water resources, which are essential for human and ecological use. The second- and third-level criteria encompassed various environmental, social, economic, and technical aspects of landfill siting, such as land use, infrastructure, engineering-geological properties, temperature, and wind direction. These criteria indicate the multiple and often conflicting factors that influence the decision-making process. The proposed method provides a flexible and adaptable framework for evaluating and comparing potential landfill sites, taking into account the local conditions and preferences. The study acknowledges the limitations and challenges of the Delphi method, such as the difficulty of selecting and recruiting experts, the potential for bias or influence among panel members, and the requirement for multiple rounds of questionnaires and feedback. However, the method can contribute to the sustainable management of solid waste and the protection of human health and the environment, by facilitating the selection of the most suitable and acceptable sites for landfilling.

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Authors' Contribution

Conceptualization: Farshad Bahrami Asl, Mohammad Taghi Samadi.
Data curation: Farshad Bahrami Asl, Seyed Elyas Amini Rabati.
Formal analysis: Yousef Poureshgh, Elnaz Alipour, Saeed Hosseinpoor.
Funding acquisition: Farshad Bahrami Asl.
Investigation: Farshad Bahrami Asl, Seyed Elyas Amini Rabati, Anahita Dehghani.
Methodology: All authors.
Project administration: Farshad Bahrami Asl.
Supervision: Farshad Bahrami Asl.
Writing-original draft: Seyed Elyas Amini Rabati, Farshad Bahrami Asl.
Writing-review & editing: Farshad Bahrami Asl.

Competing Interests

The authors declare that they have no conflict of interests.

Ethical Approval

The protocol and procedures of this study were approved by the Ethics Committee of Urmia University of Medical Sciences (IR.UMSU.REC.1400.076).

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Using Artificial Intelligence Chatbots

We utilized AI-powered tools (Gemini) to check grammar and enhance the academic quality of the text, which was primarily written by the authors.

References

1. Debrah JK, Vidal DG, Dinis MA. Raising awareness on solid waste management through formal education for sustainability: a developing countries evidence review. Recycling. 2021;6(1):6. doi: 10.3390/recycling6010006.
2. Serge Kubanza N, Simatele MD. Sustainable solid waste management in developing countries: a study of institutional strengthening for solid waste management in Johannesburg, South Africa. J Environ Plan Manag. 2020;63(2):175-88. doi: 10.1080/09640568.2019.1576510.
3. Kasthurba AK, Reddy KR. Managing Building Waste for Sustainable Urban Development: Challenges, Opportunities and Future Outlook. Hyderabad, India: Indian Institute of Technology; 2014.
4. USEPA. Basic Information about Landfills [Overviews and Factsheets]. 2023. Available from: https://www.epa.gov/landfills/basic-information-about-landfills.
5. Liu Y, Lu H, Wang C, Liu Y, Ma J, Liu M. Mechanical strength, water seepage and microstructure of a novel landfill solidified sludge liner material. Processes. 2022;10(8):1641. doi: 10.3390/pr10081641.
6. Alanbari MA, Al-Ansari N, Jasim HK. GIS and multicriteria decision analysis for landfill site selection in Al-Hashimiyah Qadhaa. Nat Sci. 2014;6(5):282-304. doi: 10.4236/ns.2014.65032.
7. Menikpura SN, Sang-Arun J, Bengtsson M. Climate co-benefits of energy recovery from landfill gas in developing Asian cities: a case study in Bangkok. Waste Manag Res. 2013;31(10):1002-11. doi: 10.1177/0734242x13492004.
8. Mirzaei M, Salman Mahiny A, Mirkarimi SH. Site selection of landfill by using analytical hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) (case study: landfill of Golpayegan township). J Nat Environ. 2014;67(1):105-19. doi: 10.22059/jne.2014.51003.
9. Sener S, Sener E, Karagüzel R. Solid waste disposal site selection with GIS and AHP methodology: a case study in Senirkent-Uluborlu (Isparta) Basin, Turkey. Environ Monit Assess. 2011;173(1-4):533-54. doi: 10.1007/s10661-010-1403-x.
10. Chabuk A, Al-Ansari N, Hussain HM, Knutsson S, Pusch R, Laue J. Combining GIS applications and method of multi-criteria decision-making (AHP) for landfill siting in Al-Hashimiyah Qadhaa, Babylon, Iraq. Sustainability. 2017 Oct 25;9(11):1932. doi: 10.3390/su9111932.
11. Mahini AS, Gholamalifard M. Siting MSW landfills with a weighted linear combination methodology in a GIS environment. Int J Environ Sci Technol. 2006;3(4):435-45. doi: 10.1007/bf03325953.
12. Oudina F, Benkhaled E, Mili M, Oudina FZ. Choosing the best site for a technical backfill center for urban solid waste using a multi-criteria evaluation technique based on geographic information systems. Case study of the city of M'sila. Technium Soc Sci J. 2022;36(1):592-606.
13. Kapilan S, Elangovan K. Potential landfill site selection for solid waste disposal using GIS and multi-criteria decision analysis (MCDA). J Cent South Univ. 2018;25(3):570-85. doi: 10.1007/s11771-018-3762-3.
14. Rezaeisabzevar Y, Bazargan A, Zohourian B. Landfill site selection using multi criteria decision making: influential factors for comparing locations. J Environ Sci (China). 2020;93:170-84. doi: 10.1016/j.jes.2020.02.030.
15. Tüdeş Ş, Kumlu KB. Solid waste landfill site selection in the sense of environment sensitive sustainable urbanization: Izmir, Turkey case. IOP Conf Ser Mater Sci Eng. 2017;245(8):082063. doi: 10.1088/1757-899x/245/8/082063.
16. Ali SA, Ahmad A. Suitability analysis for municipal landfill site selection using fuzzy analytic hierarchy process and geospatial technique. Environ Earth Sci. 2020;79(10):227. doi: 10.1007/s12665-020-08970-z.
17. Zarin R, Azmat M, Naqvi SR, Saddique Q, Ullah S. Landfill site selection by integrating fuzzy logic, AHP, and WLC method based on multi-criteria decision analysis. Environ Sci Pollut Res Int. 2021;28(16):19726-41. doi: 10.1007/s11356-020-11975-7.
18. Aksoy E, San BT. Geographical information systems (GIS) and multi-criteria decision analysis (MCDA) integration for sustainable landfill site selection considering dynamic data source. Bull Eng Geol Environ. 2019;78(2):779-91. doi: 10.1007/s10064-017-1135-z.
19. Ali SA, Parvin F, Al-Ansari N, Pham QB, Ahmad A, Raj MS, et al. Sanitary landfill site selection by integrating AHP and FTOPSIS with GIS: a case study of Memari Municipality, India. Environ Sci Pollut Res Int. 2021;28(6):7528-50. doi: 10.1007/s11356-020-11004-7.
20. Donevska KR, Gorsevski PV, Jovanovski M, Peševski I. Regional non-hazardous landfill site selection by integrating fuzzy logic, AHP and geographic information systems. Environ Earth Sci. 2012;67(1):121-31. doi: 10.1007/s12665-011-1485-y.
21. Rahimi S, Hafezalkotob A, Monavari SM, Hafezalkotob A, Rahimi R. Sustainable landfill site selection for municipal solid waste based on a hybrid decision-making approach: fuzzy group BWM-MULTIMOORA-GIS. J Clean Prod. 2020;248:119186. doi: 10.1016/j.jclepro.2019.119186.
22. Sharifi M, Hadidi M, Vessali E, Mosstafakhani P, Taheri K, Shahoie S, et al. Integrating multi-criteria decision analysis for a GIS-based hazardous waste landfill sitting in Kurdistan province, western Iran. Waste Manag. 2009;29(10):2740-58. doi: 10.1016/j.wasman.2009.04.010.
23. Zakerian S, Mokhtari M, Alhosseini Almodaresi SA. Evaluation of a landfill site using AHP and TOPSIS models: a case study of Ardakan Landfill, Iran. Avicenna J Environ Health Eng. 2015;2(1):754.

24. Ghobadi M. Environmental monitoring and assessment for landfill site selection using GIS-based SWARA and rapid impact assessment matrix. Avicenna J Environ Health Eng. 2023;10(1):57-64. doi: 10.34172/ajehe.2023.5378.
25. Linstone HA, Turoff M. The Delphi Method. Reading, MA: Addison-Wesley; 1975.
26. Rowe G, Wright G. The Delphi technique as a forecasting tool: issues and analysis. Int J Forecast. 1999;15(4):353-75. doi: 10.1016/s0169-2070(99)00018-7.
27. Hasson F, Keeney S, McKenna H. Research guidelines for the Delphi survey technique. J Adv Nurs. 2000;32(4):1008-15.
28. Zakaria B, Abdullah R, Ramli MF, Latif PA. Selection criteria using the Delphi method for siting an integrated hazardous waste disposal facility in Malaysia. J Environ Plan Manag. 2013;56(4):512-30. doi: 10.1080/09640568.2012.689614.
29. Dang J, Lal A, Montgomery A, Flurin L, Litell J, Gajic O, et al. Developing DELPHI expert consensus rules for a digital twin model of acute stroke care in the neuro critical care unit. BMC Neurol. 2023;23(1):161. doi: 10.1186/s12883-023-03192-9.
30. Shang Z. Use of Delphi in health sciences research: a narrative review. Medicine (Baltimore). 2023;102(7):e32829. doi: 10.1097/md.0000000000032829.
31. Josimović B, Marić I. Methodology for the regional landfill site selection. In: Curkovic S, ed. Sustainable Development: Authoritative and Leading-Edge Content for Environmental Management. Rijeka: IntechOpen; 2012. doi: 10.5772/45926.
32. Donevska K, Jovanovski J, Gligorova L. Comprehensive review of the landfill site selection methodologies and criteria. J Indian Inst Sci. 2021;101(4):509-21. doi: 10.1007/s41745-021-00228-2.
33. Mat NA, Benjamin AM, Abdul-Rahman S. A review on criteria and decision-making techniques in solving landfill site selection problems. J Adv Rev Sci Res. 2017;37(1):14-32.
34. Khan Z, Anjaneyulu Y. Selection of hazardous waste dumpsites based on parameters effecting soil adsorption capacity–a case study. Environ Geol. 2003;43(8):986-90. doi: 10.1007/s00254-002-0723-8.
35. Simsek C, Kincal C, Gunduz O. A solid waste disposal site selection procedure based on groundwater vulnerability mapping. Environ Geol. 2006;49(4):620-33. doi: 10.1007/s00254-005-0111-2.
36. Milovanovic M. Water quality assessment and determination of pollution sources along the Axios/Vardar River, Southeastern Europe. Desalination. 2007;213(1-3):159-73. doi: 10.1016/j.desal.2006.06.022.
37. Gorsevski PV, Donevska KR, Mitrovski CD, Frizado JP. Integrating multi-criteria evaluation techniques with geographic information systems for landfill site selection: a case study using ordered weighted average. Waste Manag. 2012;32(2):287-96. doi: 10.1016/j.wasman.2011.09.023.
38. Fallahpour M, Jafari HR, Karimi S, Makhdoum M. Application of Delphi method for criteria prioritization in hazardous waste landfill site selection in Iran. J Multidiscip Eng Sci Technol. 2016;3(7):5202-7.
39. Ghaed Rahmat Z, Vosoughi Niri M, Alavi N, Goudarzi G, Babaei AA, Baboli Z, et al. Landfill site selection using GIS and AHP: a case study: Behbahan, Iran. KSCE J Civ Eng. 2017;21(1):111-8. doi: 10.1007/s12205-016-0296-9.
40. Pasalari H, Nabizadeh Nodehi R, Mahvi AH, Yaghmaeian K, Charrahi Z. Landfill site selection using a hybrid system of AHP-Fuzzy in GIS environment: a case study in Shiraz city, Iran. MethodsX. 2019;6:1454-66. doi: 10.1016/j.mex.2019.06.009.
41. Chabuk A, Al-Ansari N, Hussain HM, Knutsson S, Pusch R. Landfill site selection using geographic information system and analytical hierarchy process: a case study Al-Hillah Qadhaa, Babylon, Iraq. Waste Manag Res. 2016;34(5):427-37. doi: 10.1177/0734242x16633778.
42. Khorsandi H, Faramarzi A, Aghapour AA, Jafari SJ. Landfill site selection via integrating multi-criteria decision techniques with geographic information systems: a case study in Naqadeh, Iran. Environ Monit Assess. 2019;191(12):730. doi: 10.1007/s10661-019-7863-8.
43. Karimi H, Amiri S, Huang J, Karimi A. Integrating GIS and multi-criteria decision analysis for landfill site selection, case study: Javanrood county in Iran. Int J Environ Sci Technol. 2019;16(11):7305-18. doi: 10.1007/s13762-018-2151-7.
44. Rueda-Avellaneda JF, Gomez-Gonzalez R, Rivas-García P, Benitez-Bravo R, Botello-Álvarez JE, Wang Z. Application of a sustainable location index approach to landfill site selection in Monterrey, Mexico. Waste Manag Res. 2023;41(5):1014-25. doi: 10.1177/0734242x221138733.