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RESEARCH ARTICLE

Decision-making for the selection of different leachate treatment/management methods: the ANP and PROMETHEE approaches

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Abstract

Municipal solid waste (MSW) landfill leachate is a highly contaminated liquid effluent. Leachate has a complex nature that needs to be appropriately treated before being discharged into the environment. There are various options for leachate treatment. Deciding which option should be applied is a complex process, since it depends on many factors that need to provide a balance between the technical, economic, and environmental aspects of sustainability. Multi-criteria decision-making (MCDM) methods are useful techniques to solve complex problems that cannot be easily solved. In this study, MCDM techniques are used for an evaluation of four different leachate treatment options: recirculation of leachate to a landfill site (A1), combined treatment with municipal wastewater (A2), anaerobic and aerobic sequential treatment (A3), and advanced leachate treatment based on membrane processes (A4). The selection of the most appropriate one, based on the criteria, analytic network process (ANP), and preference ranking organization method for enrichment evaluations (PROMETHEE) methods, was applied as MCDM techniques using the Super Decisions software and D-Sight software, respectively. Both the ANP and the PROMETHEE analysis results demonstrate that option A2 is the most appropriate for all of the decision-makers.

Keywords Analytic network process (ANP) · Leachate treatment · Multi-criteria decision-making (MCDM) · Preference ranking organization method for enrichment evaluations (PROMETHEE)

Introduction

Landfill is one of the most widely used methods of disposal in municipal solid waste (MSW) management. MSW management has become difficult, owing to an exponential increase in solid waste amounts in recent decades. In 2016, almost 37% of waste was disposed of in landfills around the world. Nearly 19% was recovered through recycling and composting, and 11% was treated through incineration. Despite this, 30% of waste worldwide was still openly dumped (World Bank Group 2018). The number of landfill sites has rapidly increased throughout the world, and this has led to a need for leachate treatment facilities. Leachate treatment is a major issue of landfill management. Many factors affect leachates composition, such as landfill age, climate conditions, waste types, and waste compositions. Generally, landfill leachate characteristics are chemical oxygen demand (COD), suspended solids (SS), ammonium nitrogen (NH_4-N), heavy metals content, and pH. There are various options for leachate treatment, and these can be classified into five groups: leachate recycling or recirculation to landfill, channeling (combined treatment with municipal wastewater), biological (aerobic or anaerobic) processes, physical-chemical processes (include air stripping, coagulation, flocculation, precipitation, chemical oxidation process, adsorption, ion exchange, electrochemical processes and flotation), and membrane processes (microfiltration, ultrafiltration, nanofiltration, and reverse osmosis). Among these, recycling or recirculation of leachate to landfill has been widely used in many landfills since it is one of the least expensive approach options available.

Abbas et al. (2009) report that leachate recirculation increases the moisture content of a process and supplied solid or liquid methanogens for the delivery of nutrients and

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enzymes. A Talalaj (2015) study demonstrated that the concentration of organic compounds increased during the initial period of recirculation, but their values stabilized after 6 months. The author found that the recirculation to a landfill process produces a higher leachate concentration, in particular in terms of $N\text{-}NH_4$, and Cl^-. The combined treatment of leachate with municipal wastewater is another commonly used leachate management option. This option usually preferred, owing to its easy maintenance and low operating costs. Although this option eliminates the nutrient addition to the treatment process, organic inhibitory compounds and heavy metals in the leachate might decrease treatment efficiency (Renou et al. 2008). Biological treatment processes can be classified as aerobic and anaerobic, depending on whether or not the biological processing needs an oxygen supply. These treatment processes are very useful methods to eliminate resistant organic biodegradables found in the leachate. The physical and chemical processes enable the removal of non-biodegradable part of the leachate and unsuitable compounds from the landfill leachate and precipitate heavy metals found there (Vedaraman et al. 2013). Together with biological approaches, these methods are preferred to enhance treatment performance or to treat a particular pollutant. Membrane filtration can be categorized as various filtration techniques for membranes; microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are used in the treatment of landfill leachate. Generally, membrane filtration aims to remove pollutants, such as suspended solids, compounds of high molecular weight, hardness ions, and sulfate salts (Abbas et al. 2009).

Multi-criteria decision-making (MCDM) techniques are effective tools for applications designed to solve multiple-choice problems. According to a review that scanned from 2000 to 2014, realized by Mardani et al. (2015), MCDM techniques have been used in areas of energy-environment-sustainability, supply chain and quality management, materials, project management, security and risk management, manufacturing systems, production management, operational research and soft computing, technology management, strategic management, tourism management, knowledge management, and other areas. Among these, the application field of energy-environment-sustainability had a maximum share with 13.45%, Mardani et al. (2015).

Environmental application of MCDM methods was further researched from 2014 to 2019 with the key words, “MCDM and waste.” The percentile distributions of the application areas are given in Table 1.

Among the application areas, it can be seen that only approximately 4% are based on wastewater treatment. For this reason, the research was extended to 2009, and detected wastewater treatment-related MCDM studies are listed in Table 2. Among these, analytical hierarchy process (AHP) is the most common. The AHP is dependent on the fact that the inherent complexity of the MCDM problem can be resolved by building hierarchical structures, including an objective, requirements, and alternatives (Aragones-Beltran et al. 2009). AHP is a method that uses a hierarchical structure to assess the relative importance of the criteria depending on a binary comparison. A precondition of the hierarchical structure is that the precedence of each level’s criteria should not depend on the criteria of the lower level. On the contrary, the AHP method is indeterminate, and its results are not trustworthy. Therefore, the analytic network process (ANP) was exhibited dependent on the super-matrix technique in order to modify this process. Decision-makers are able to determine depending on the intra and interrelationship of the criteria at various levels of the decision-making procedure to solve sophisticated problems with a non-categorization framework using this technique (Soroudi et al. 2018). According to Saaty (Saaty 2004), although the AHP and the ANP assist in unfolding the complexity, the ANP has greater depth and more widely usable applications. For these reasons, the ANP method was applied in this study. In addition to the ANP, the PROMETHEE method was also used, since it allows the selection of an assessment variable to be specified or the assessment variable to be limited to the values defined by it (Ozturk 2018).

In literature studies, the ANP method was only used by Ratnawati et al. (2019) to select the best alternative among three different leachate treatment options; coagulation-flocculation, activated sludge, and anaerobic treatment were considered. On the other hand, according to the authors’ best knowledge, there has been no paper in the literature which discusses the application of the PROMETHEE method in making a decision for landfill leachate treatment. Therefore, it is thought that this study will fill a gap in the literature using the ANP and PROMETHEE methods to decide between the different leachate treatment alternatives. For this, firstly, four different leachate treatment alternatives from the leachate examination commission report were determined according to actual implementations of landfill leachate management (MEU 2011). Next, the criteria of evaluation were chosen in terms of technical, environmental, and cost. It was considered that the evaluation was carried out by three different decision-makers: the municipality, the landfill operator site, and the local community.

Materials and methods

In this study, two different MCDM methods, ANP and PROMETHEE, were applied in order to prioritize different alternatives. Not only the same alternatives and but also the same criteria were used for resolving the problem in both methods. A definition of decision-maker is crucial in MCDM studies. A decision-maker might be a person or a group of experts (for example, a council or a committee) making an ultimate choice between alternatives. The evaluations

Table 1 Distribution of literature studies regarding MCDM applications on waste management

Application field	Number of papers	Percentage
Construction and demolition waste management	2	1.94
Domestic food waste management	1	0.97
ELV waste management	1	0.97
E-waste management	3	2.91
Hazardous waste management	4	3.88
Healthcare waste treatment	17	16.50
Industrial waste	2	1.94
Mine waste management	1	0.97
Nuclear waste management	1	0.97
Selection of transmission firms (hazardous waste, healthcare waste)	4	3.88
Site selection for waste management (municipal, healthcare waste, electronic waste, hazardous waste, and so on)	29	28.16
Solid waste collection system selection	1	0.97
Solid waste management	34	33.01
Wastewater treatment	4	3.88
Total	103	100.00

Source: Author's calculation from Google Scholar

were conducted by three different decision-makers: the municipality, the operator of landfill site, and the local community in this study. A flowchart of the study is presented in Fig. 1.

Characteristics of leachate

The initial characteristic features of leachate were determined considering the "Leachate Commission Report," which was published in regard to the leachate treatment system in Turkey (MEU 2011). According to this report, leachate flow rate, COD, SS, BOD, and total nitrogen values were chosen as 600 m^3/day, 27,500 mg/L, 15,000 mg/L, 2000 mg/L, and 2000 mg/L, respectively. The landfill characteristics and treatment processes are given in Table 3.

Description of the alternatives

Alternative leachate treatment methods were determined according to the leachate examination commission report (MEU 2011). The alternatives are as follows: recirculation of leachate to the landfill site (A1), combined treatment with municipal wastewater (A2), anaerobic and aerobic sequential treatment (A3), and advanced leachate treatment based on membrane processes (A4). The alternatives to leachate treatments are illustrated in Fig. 2 and are described in the following way.

Definition and weighting of criteria

The same criteria were used for both the ANP and the PROMETHEE methods (Table 1), but they were clustered as "benefit, cost, and risk" for the ANP method, whereas they were clustered as "environmental, economic, and technical" for the PROMETHEE method. The criteria and their clusters, unit, and remarks are given in Table 4.

The percentile weightings of each of the criteria corresponding to the decision-makers are given in Table 5. Both the ANP and the PROMETHEE analysis, the percentile weights of each cluster and each of the criteria, are defined based on the opinion of experts from the municipality, the landfill, and the local community. For scoring importance of each of the criteria, the experts ranked their percentile in the following manner. The environmental criteria cluster g_1 (COD), g_2 (SS), g_3 (ammonia removal efficiency), and g_8 (odor problem) were weighted as 4k, 2k, 2k, and k respectively. In the economic criteria cluster g_5 (installation costs), g_6 (operation costs), and g_7 (residual waste treatment costs) were weighted as 3l, 3l, and 2l, respectively. Lastly, in the technical criteria cluster g_4 (installation period), g_8 (exposure to climate conditions), and g_{10} (ease of application) were considered as having equal weighting (m, m, m) for each of the criteria, respectively.

In the PROMETHEE analysis, according to the perspective of the municipality, the prioritization of clusters was ranked as the economic (1: first), the technical (2: second), and the environmental (3: third). For the landfill operator site, the prioritization was considered to be the technical (1), the economic (2), and the environmental (3) criteria, respectively. Lastly, the prioritization of criteria for the local community was considered as the environmental (1), the technical (2), and the economic (3). It was decided that the first priority rank criteria cluster takes 50% weighting overall, the second priority rank cluster takes 30% weighting overall, and the third priority rank cluster takes 20% weighting overall; for instance, the

Table 2 Wastewater treatment-related MCDM studies

References	MCDM method	Water type	Alternatives	Result
Aragones-Beltran et al. (2009)	AHP[a] and PROMETHE[b]	Textile wastewater	Eight different coagulant concentrations were chosen based on COD concentration.	-Coagulant B is the most appropriate alternative among chemicals in the physical-chemical wastewater treatment process.
Abu Qdais (2010)	AHP	Landfill leachate	Five landfill leachate management alternatives.	The onsite treatment option ranked the most preferable. The discharge without treatment and evaporation alternatives were not appropriate to selection because of higher environmental and potential health risks.
Karimi et al. (2011)	TOPSIS[c] and Fuzzy AHP methods	Industrial wastewater	Five different (UASB[f], UAFB[g], ABR[h], Contact Anaerobic Process, Anaerobic Lagoon) anaerobic wastewater treatment process.	-The results of these two methods were very similar to each other, and UAFB and ABR were the appropriate anaerobic treatment process for industrial estates in Iran.
Martin-Utrillas et al. (2015)	Hybrid method (AHP Delphi-VIKOR)	Leachate treatment in waste treatment plant	To select an optimum process of leachate treatment in waste treatment regarding six different alternatives.	-The model proposed a solution as a hybrid treatment of a biological treatment, a chemical oxidation, an ultrafiltration, and an activated carbon process. -Lagooning has full rejection
Biglarijoo et al. (2017)	AHP	Leachate	Two alternative catalyst (iron (II) sulfate ($FeSO_4$) and iron (III) chloride: $FeCl_2$).	-AHP showed $FeCl_2$ as a proper catalyst in comparison with $FeSO_4$, owing to the environmental risk value and lower sludge generation.
Saha et al. (2017)	NSFDSS[d]	Municipal wastewater	Eight alternatives were weighted to determine their importance for the treatment efficiency. • Amount of intake water • Time of treatment • Discharge ratio • Amount of output water • Efficiency of clariflocculator • Efficiency of filter bed • Efficiency of chlorination unit • Channel efficiency	-The results obtained from the application of the NSFDSS shows that the efficiency of clarifloccculator is the most sustainable parameter for the water treatment plant.
Anoakar et al. (2018)	TOPSIS	Municipal wastewater	Efficiency of six numbers of municipal wastewater treatment plants was compared on the basis of BOD[i], COD, TDS[j], SS[k], Nitrogen, and Cl removal.	-WWTP2[l], with a score of 0.455, was ranked first, indicating the highest efficiency, whereas WWTP4, with a score of 0.649, was ranked sixth when assessed on the basis of the Central Pollution Control Board of India limits.
Choudhury et al. (2018)	Hybride method of DEMATEL[e]-NSF-DSS	Drinkable water	Eight alternatives were weighted to determine their importance for the treatment efficiency. • Amount of intake water per day • Time of treatment • Discharge rate • Amount of output water • Efficiency of clariflocculator • Efficiency of filter bed • Efficiency of chlorination unit • Channel efficiency	-The results demonstrate that among all the parameters selected, the efficiency of the clariflocculator is the most important parameter.
Zhang et al. (2019)	AHP	Leachate concentrate treatment	Six different current membrane concentrate treatment technologies, which include advanced oxidation and evaporation.	-Submerged combustion evaporation options are determined to be the most cost-effective.

[a] Analytical hierarchy process

[b] Preference ranking organization method for enrichment evaluations

[c] Technique for order preference by similarity to ideal solution

[d] Non-structural fuzzy decision support system

[e] The decision-making trial and evaluation laboratory method

[f] Upflow anaerobic sludge bed

[g] Upflow anaerobic fixed bed

[h] Anaerobic baffled reactor,

[i] Biochemical oxygen demand

[j] Total dissolved solids

[k] Suspended solids

[l] Wastewater treatment plant

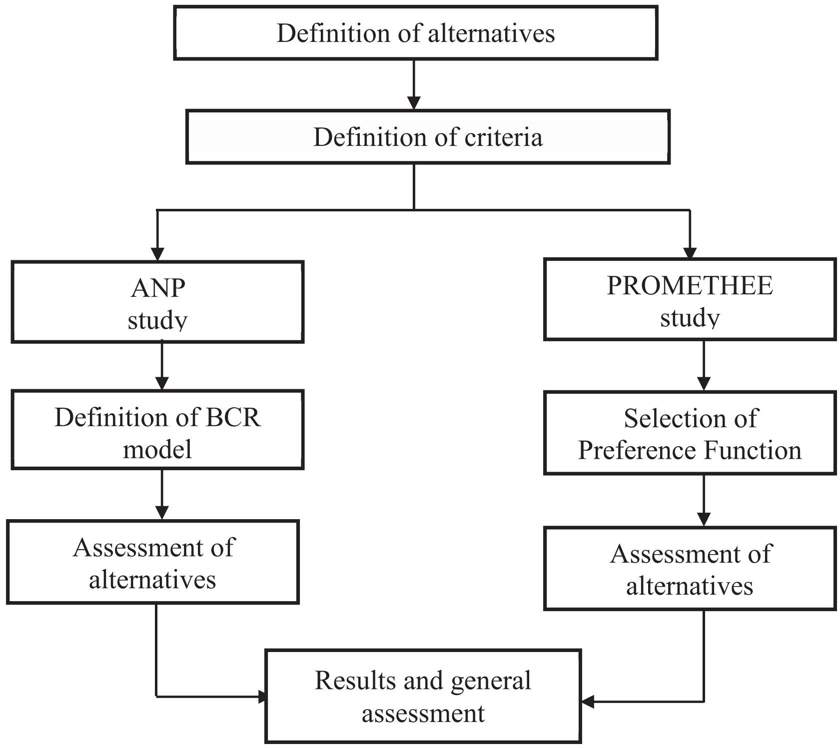

Fig. 1 Flow chart of the study

importance level of clusters for the municipality was determined as economic (50%), technical (30%), and environmental (20%), in the weighting step.

In the ANP analysis, the clusters are benefit, cost, and risk due to the use of the BCR model. Therefore, the g4 criteria, which belonged to the technical cluster in the PROMETHEE analysis, were evaluated in the benefit cluster for the ANP analysis. Similarly, the g8 criteria were considered in the risk cluster for the ANP analysis, whereas these criteria were included in the environmental cluster in the PROMETHEE analysis. At this point, the percentile of weightings of criteria in the ANP analysis was carried out as in the PROMETHEE analysis and only the percentile of the weights of the clusters, to which g4 and g8 belonged, changed.

Methodological study

ANP methodology

The ANP is a complete decision-making tool that has the means to consider all related criteria (Jharkharia and Shankar 2007). The ANP contributes a comprehensive structure that covers clusters of linked elements in any required way to examine the process of obtaining priority proportion scales and forms the distribution of effect between clusters and elements. There are two parts of the ANP. The first part is a hierarchy control or network of criteria and sub-criteria that control the interactions in the system being studied. The second part is a network of influences among the elements and clusters. The network changes from criteria to criteria, and a super matrix of limitation of influence is calculated for each control criteria. A super matrix is a matrix of elements of two dimensions. The priority vectors of the paired comparisons are placed in the appropriate column of the super matrix. Since the super matrix is built in this way, the total of each column corresponds to the number of sets of comparison. Ultimately, each of this super matrixes is weighted by its control criterion's priority, and all control parameters (criteria) are applied to synthesize performance. Therefore, a problem is widely analyzed through a hierarchy of control; first is the benefits of system, second is the costs, third is the opportunity, and fourth is the risk. The synthesized outcomes of the four control systems are combined by taking the gain quotient times the costs, the opportunities, and the risks in order to conclude with the best result (Ulutaş-Haktanırlar 2005). In the ANP, relative values of importance are calculated using binary correlation using a scale of 1–9, in which a score of 1 indicates fair significance among the two elements, and 9 represents extreme significance of one element compared with the other.

In this study, before the methodological applications, performance values of each of the criteria for the leachate treatment alternatives were determined. Criteria with units were determined based on studies from the literature (g1–g3 and g5–g7). Criteria with scores (g4 and g8–g10) were determined by expert groups (EG) according to relative importance values.

Table 3 Leachate treatment processes and leachate characteristics in Turkey

Treatment process	Design parameters				
	Flow rate, m^3/day	COD, mg/L	BOD_5 mg/L	Total N mg/L	TSS mg/L
Reverse osmosis	50	24,950	n.a	1065	1380
Reverse osmosis	600	48,000	34,000	3000	n.a
Reverse osmosis	n.a	28,000	15,000	2800	2000
Membrane bioreactor + nanofiltration	2000	20,000	13,000	3000	1500
Membrane bioreactor + nanofiltration	50	20,000	13,000	3000	1500
Anaerobic + aerobic	200	50,000	40,000	3000	n.a
Anaerobic + aerobic	45	8137	11,487	1000	600
Aerobic + facultative + sequence batch reactor	500	30,000	15,000	1500	n.a
Aerobic + facultative + sequence batch reactor	22	26,000	10,500	823	3790

n.a., not available

The structure of the ANP model was performed via the Super Decision software. The ANP model comprised two parts: a criteria network and a network of the interaction between clusters and criteria. The aim was carried out considering a benefit, cost, and risk analysis according to performance values (shown in Table 5). Between g1–g3 criteria and g5–g7 criteria, direct data was entered; however, a scoring method for the other criteria through pairwise comparison was applied. In addition, inconsistency ratios were less than 10%, owing to the nature of the method. The importance of the weighting of the selected criteria is defined by a formula as a reciprocal in the program:

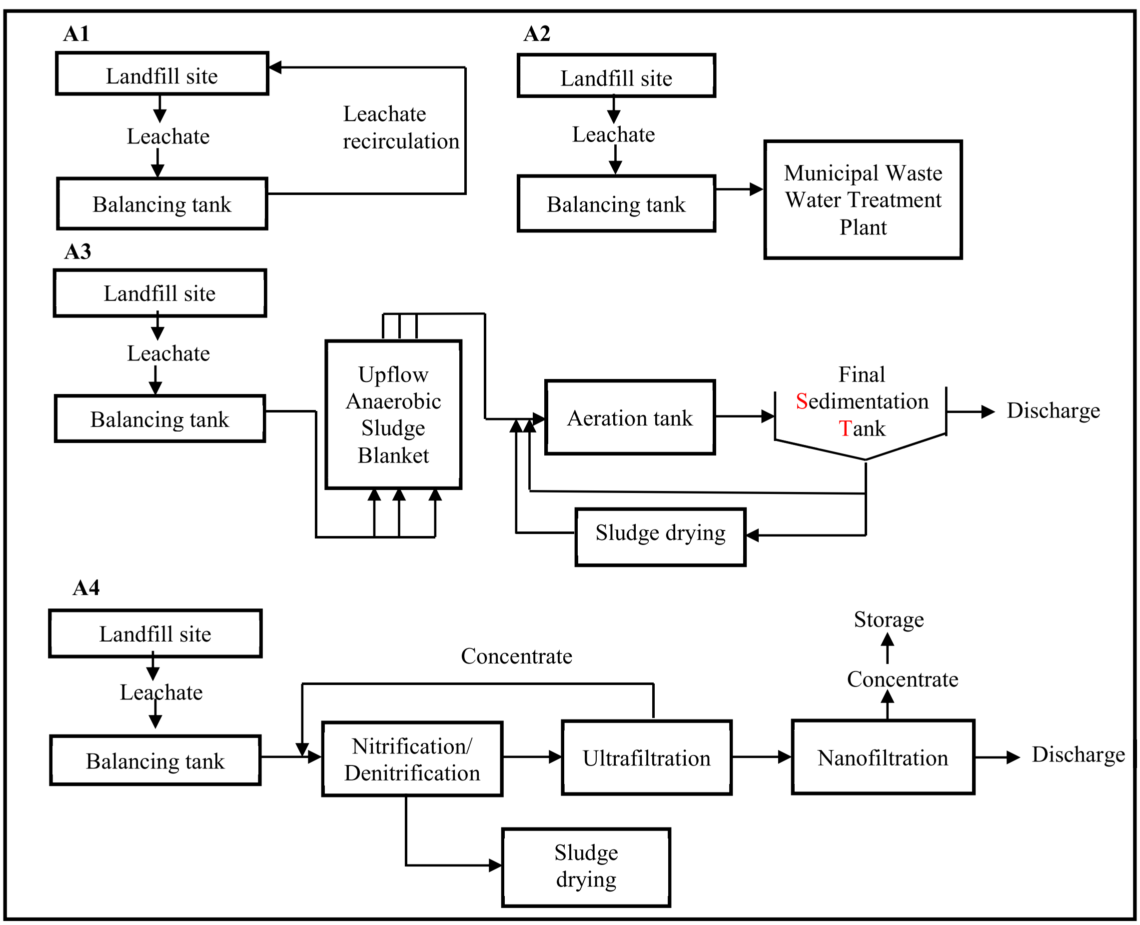

Fig. 2 Process flow charts of leachate treatment alternatives

Table 4 Criteria and specifications used in the ANP and PROMETHEE methods

No	Name	Cluster		Unit/score	Remarks
		ANP	PROMETHEE		
g1	Chemical oxygen demand (COD) removal efficiency	Benefit	Environmental	%, increasing	For these criteria, the removal efficiencies of the pollutants were evaluated before the leachate was given to the recipient environment.
g2	Suspended solids (SS) removal efficiency	Benefit	Environmental	%, increasing	
g3	Ammonia removal efficiency	Benefit	Environmental	%, increasing	
g4	Installation period	Benefit	Technical	Score (1–9), decreasing	These criteria take into account an installation/construction period of treatment alternatives.
g5	Capital cost	Cost	Economic	\$/ton, decreasing	This includes infrastructure and equipment for capital cost.
g6	Operation cost	Cost	Economic	\$/ton, decreasing	This includes energy, water, and labor costs.
g7	Residual/waste cost	Cost	Economic	\$/ton, decreasing	These criteria consider costs arising from the treatment of the occurred residuals after the treatment process; the residuals are known to be dangerous in some cases.
g8	Odor problem	Risk	Environmental	Score (1–9), decreasing	These criteria take into account the environmental effect of smells that may be produced near the treatment facility.
g9	Exposure to climate conditions	Risk	Technical	Score (1–9), decreasing	These criteria take into account influence of climate (temperature, precipitation, etc.) on the alternatives.
g10	Ease application	Risk	Technical	Score (1–9), increasing	These criteria consider difficulties for both constructor and operators during the installation and operation stages of the alternatives.

$$\text{Formula}: bB + oO + c(1-C) + r(1-R) \quad (1)$$

where B is benefit, O is opportunity, C is cost, and R is risk, with values of benefit (b), opportunity (o), cost (c), and risk (r) determined according to Table 6. Each decision-maker has different b, c, and r of values in this study. The opportunity cluster does not exist regarding the chosen criteria. In accordance with this, each cluster is initially evaluated independently. These ratings are then aggregated using the weighting of the cluster and the formulas, including that used to multiply the benefit ratios, cost, and risk ratios reciprocals. The obtained raw results are normalized in the last step, and the values can be used as percentages in order to evaluate the alternatives.

Table 5 Evaluation process of criteria weights (%) for different decision-makers

Cluster	Criteria	ANP			Cluster	Criteria	PROMETHEE		
		Mun.[1]	OLS[2]	LC[3]			Mun.[1]	OLS[2]	LC[3]
Benefit cluster	g1	8.90	8.90	22.20	Environmental cluster	g1	8.90	8.90	22.20
	g2	4.44	4.44	11.10		g2	4.44	4.44	11.10
	g3	4.44	4.44	11.10		g3	4.44	4.44	11.10
	g4	10.00	16.67	10.00		g8	2.22	2.22	5.60
Economic cluster	g5	18.75	11.25	7.50	Economic cluster	g5	18.75	11.25	7.50
	g6	18.75	11.25	7.50		g6	18.75	11.25	7.50
	g7	12.50	7.50	5.00		g7	12.50	7.50	5.00
Risk cluster	g8	2.22	2.22	5.60	Technical cluster	g4	10.00	16.67	10.00
	g9	10.00	16.67	10.00		g9	10.00	16.67	10.00
	g10	10.00	16.67	10.00		g10	10.00	16.67	10.00

[1] Municipality

[2] Operator of landfill site

[3] Local community

Table 6 Performance value of each alternative

Criteria	Unit/score	Alternatives			
		A1	A2	A3	A4
g1	%	65 (Gupta and Singh 2007)	90 (Renou et al. 2008)	92.5 (Lin et al. 2000); (Abbas et al. 2009)	99 (MEU 2011)
g2	%	50 (Gupta and Singh 2007)	75 (Torretta et al. 2016)	85 (Renou et al. 2008)	90 (MEU 2011)
g3	%	10 (Sponza and Ağdağ 2004)	40 (Torretta et al. 2016)	80 (Renou et al. 2008)	99 (MEU 2011)
g4	Points (1–9)	4 determined by EG	2 determined by EG	6 determined by EG	8 determined by EG
g5	$\$/m^3$	0.9 (Gupta and Singh 2007)	0.45[a] assumed	1.6[b] (Öztürk 2016)	2.3 (MEU 2011)
g6	$\$/m^3$	0.3 (Gupta and Singh 2007)	1.0[c] (IWSA 2013)	1.2[b] (Öztürk 2016)	6.1 (MEU 2011)
g7	$/t	0.6[d] calculated	0.6[d] calculated	9.6[d] calculated	10.2[d] calculated
g8	Points (1–9)	4 determined by EG	2 determined by EG	6 determined by EG	8 determined by EG
g9	Points (1–9)	8 determined by EG	6 determined by EG	4 determined by EG	2 determined by EG
g10	Points (1–9)	2 determined by EG	4 determined by EG	6 determined by EG	8 determined by EG

[a] The installation cost was assumed to be 50% of A1

[b] Wastewater treatment plant costs were obtained from Öztürk's (2016)

[c] This was calculated according to IWSA's Regulation of Wastewater Discharge to Sewage System, Article: 11

[d] The cost of sludge treatment per amount of sludge was obtained from a study by Özön and Kılıçaslan (2012)

PROMETHEE methodology

The PROMETHEE method is one of the most common multi-criteria decision-making techniques. The PROMETHEE method provides interesting features, such as decreased recompose impact or its direct data process that does not require any previous normalization. The use of preference thresholds to determine to what degree evaluation differences are important in constructing the decision-maker's preferences is a useful tool when unclear information data or calculation errors are concerned (Aragones-Beltran et al. 2009). In the PROMETHEE method, the preference function converts the difference between two alternatives into a preference degree for each criterion. This degree is between 0 to 1 (Osmanbasoglu et al. 2019). There are six types of preference function that are usual type, U-type, V-type, level, linear, and Gaussian. For each criterion, there is a sensitivity threshold (q) if the function type is U-type, a preference threshold (p) if the function is V-type or Gaussian, and both sensitivity and preference thresholds should be defined if the function is linear or level.

In order to carry out the PROMETHEE method, units, maximum/minimum option, function types, and selection of threshold values of certain criteria are summarized in Table 7. In addition, the Gauss function is chosen in the criteria used in numerical value, while the ordinary (usual) type function is used in the qualitative criteria rated as 1–9. For the Gauss function, threshold values were determined by decision-makers; however, there is no threshold value in the ordinary function. For a PROMETHEE analysis, the values in Tables 5–7 were inserted into the D-Sight software in order to make an analysis regarding the prioritization of alternatives.

Results and discussion

ANP results

The results of the ANP method correspond to the clusters (benefit, cost, and risk), and the aggregated outcomes of the clusters (overall), according to the perspectives of three different decision-makers, are shown in Fig. 3. A maximum of benefit and cost and a minimum of risk values are more appropriate in the ANP analysis results. According to this, the most suitable alternative for the benefits cluster is the advanced leachate treatment based on membrane processes (A4) (32.4%), whereas a combined treatment with municipal wastewater (A2) (8.7% and 23.6%) is the most suitable for cost and risk clusters as shown in Fig. 3. The benefit cluster values also changed range from 16.4 to 32.4%; A4 shows the highest benefit compared with other alternatives, because A4 has an advanced/further leachate treatment based on membrane processes (by ultrafiltration and nanofiltration) reaching higher environmental efficiency. The cost values, ranging from 8.7 to 55.6% and A2 show the lowest cost value. However, A2 and A1 (8.8%) options are similar to each other in terms of the cost criteria. In the risk cluster, the values of risk change range from 23.6 to 26.4%. These values are extremely close, due to criteria value balancing according to Table 5. In addition, overall results, which are aggregated based on the weight of clusters, show that a combined treatment with municipal wastewater (A2) is the most appropriate alternative from all of the decision-maker perspectives. It is thought that the reason behind the priority of A2 results from its lower impact on cost and risk clusters against benefit.

Table 7 Criteria properties

Criteria	Min./max.	Function type	Absolute (A)/relative (R)	Preference threshold values
Environmental criteria				
g1 COD removal efficiency	Max.	Gauss	A	10
g2 SS removal efficiency	Min.	Gauss	A	15
g3 ammonia removal efficiency	Max.	Gauss	A	20
g8 odor problem	Min.	Ordinary	R	-
Economic criteria				
g5 installation cost	Min.	Gauss	A	1
g6 operation cost	Min.	Gauss	A	1
g7 residual waste treatment cost	Min.	Gauss	A	3
Technical criteria				
g4 Installation period	Min.	Ordinary	R	-
g9 exposure to climate conditions	Min.	Ordinary	R	-
g10 ease application	Max.	Ordinary	R	-

PROMETHEE results

The results of the PROMETHEE analysis for three decision-makers are summarized in Fig. 4. In the PROMETHEE analysis, the highest positive score represents the most appropriate alternative from the perspectives of all of the discussed decision-makers. These ranking values demonstrate that the combined treatment with municipal wastewater (A2) is the most appropriate method for the three decision-makers. Additionally, in the PROMETHEE analysis, the sum of negative ranking values and positive ranking values of each alternative should be equal to zero. In this case, an A1 negative ranking value equals the sum of the other alternatives' positive values from the perspective of the second and third decision-maker. From the position of the municipality, A1 and A4 have negative ranking values compared with A2 and A3. The reason for this finding is based on the fact that the importance level of criteria for the municipality was selected as economic (50%), technical (30%), and environmental (20%) in the weighting step. Additionally, A4 demonstrates higher economic values and A1 shows lower environmental performance compared with the other alternatives in Fig. 5. A1 is the worst alternative due to its low economic and environmental performance in the weighting stage. From the perspective of the second decision-maker as the operator of the landfill site, the weighting level was chosen as technical (50%), economic (30%), and environmental (20%) sides. Figure 4 shows that A1 is the worst option, because it performed at a lower environmental performance and lower technical appropriation compared with the others (as shown in Fig. 5). From a local

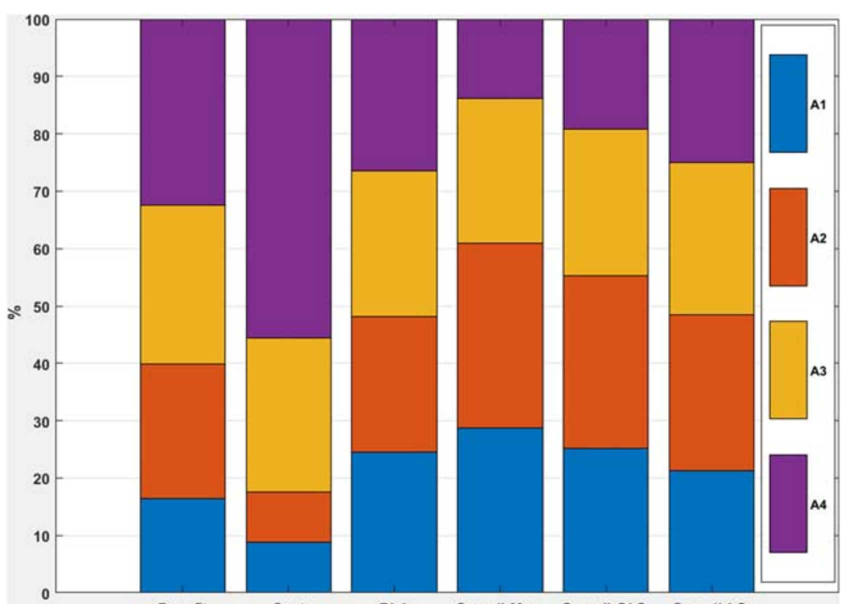

Fig. 3 ANP results in terms of benefit, cost, risk, and overall from the perspective of each decision-maker. The recirculation of leachate to the landfill site (A1), combined treatment with municipal wastewater (A2), anaerobic and aerobic sequential treatment (A3), and advanced leachate treatment based on membrane processes (A4). Mun., municipality; OLS, operator of landfill site; LC, local community

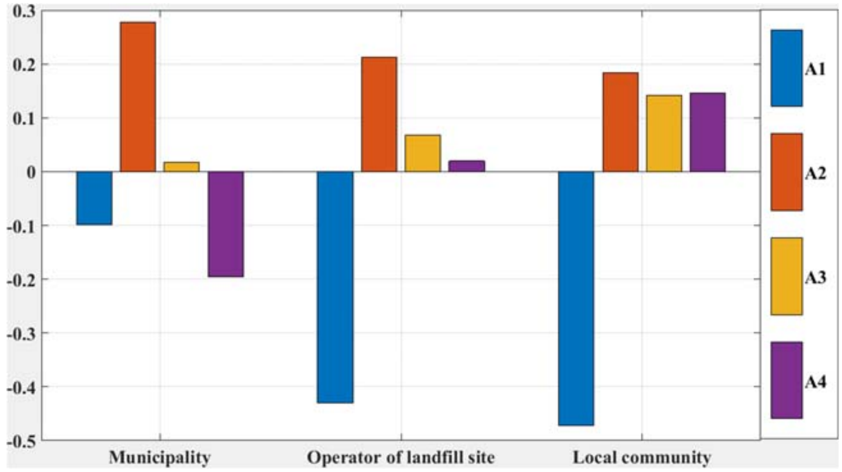

Fig. 4 Ranking of the alternatives with the PROMETHEE method. Recirculation of leachate to the landfill site (A1), combined treatment with municipal wastewater (A2), anaerobic and aerobic sequential treatment (A3), and advanced leachate treatment based on membrane processes (A4)

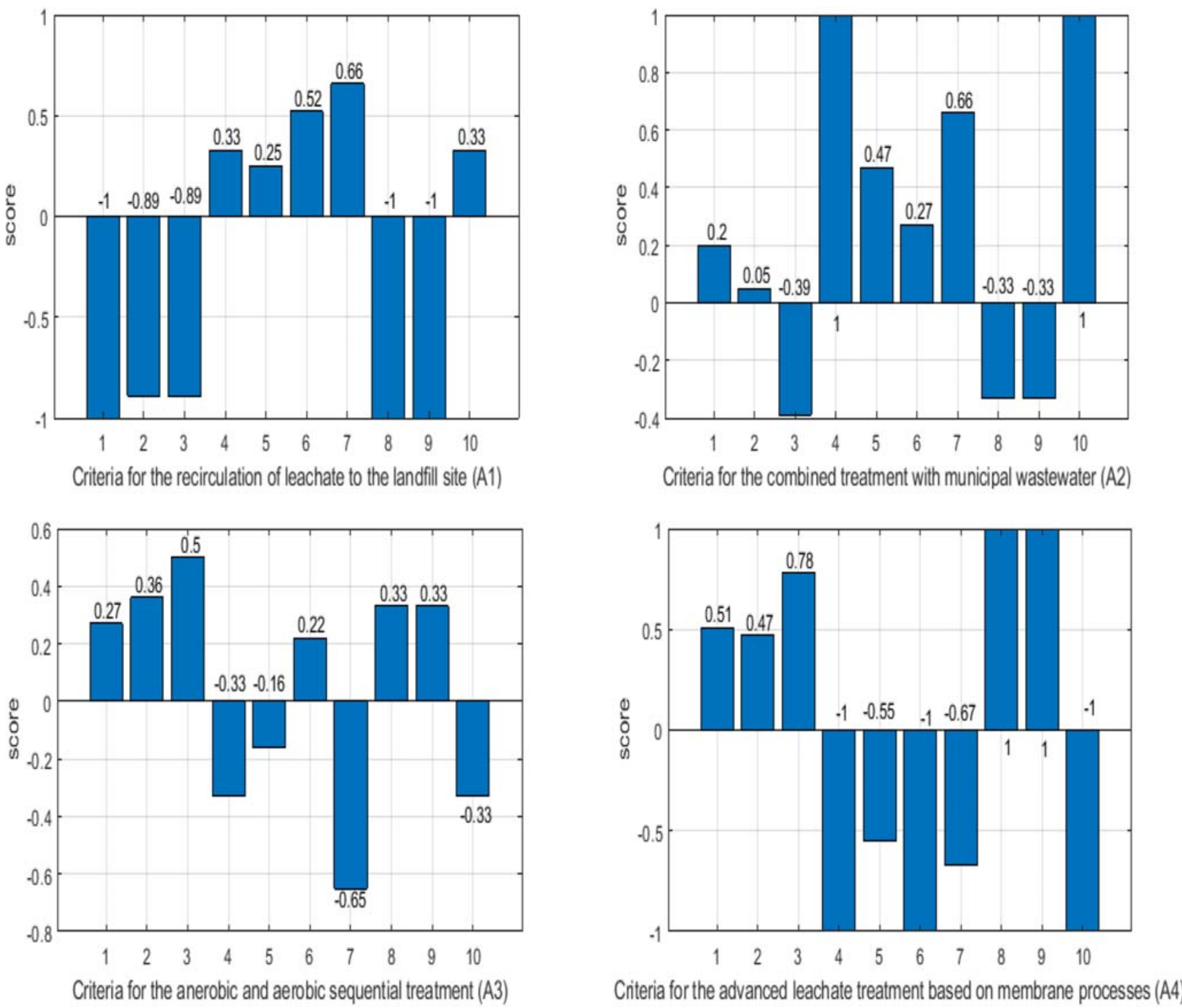

Fig. 5 The effects of criteria to alternatives. 1 COD removal efficiency. 2 SS removal efficiency. 3 Ammonia removal efficiency. 4 Odor problem. 5 Capital cost. 6 Operational cost. 7 Residual waste cost. 8 Ease application. 9 Exposure to climate conditions. 10 Installation period

Table 8 A comparison results of leachate treatment alternatives with the ANP and PROMETHEE analyses

Alternatives	Ranking-ANP			Ranking-PROMETHEE		
	Mun.	OLS.	LC.	Mun.	OLS.	LC.
Recirculation of leachate to the landfill site (A1)	2	3	4	3	4	4
Combined treatment with municipal wastewater (A2)	1	1	1	1	1	1
Anaerobic and aerobic sequential treatment (A3)	3	2	2	2	2	3
Advanced leachate treatment based on membrane processes (A4)	4	4	3	4	3	2

Mun., municipality; *OLS*, operator of landfill site; *LC*, local community

community perspective, A2 has the highest ranking value rather than A3 and A4, whereas A1 is the weakest appropriate option. The local community considers weighting criteria as being mainly environmental at 50%, technical criteria at 30%, and economic at 20%. A2 has a slightly higher ranking value than A3 and A4. The reason is that A2 has a low cost value and better technical feasibility.

The acquired ranking results from both the ANP and PROMETHEE methods are compared in Table 8. In the results of these methods, it is shown that the combined treatment with municipal wastewater (A2) is the most appropriate option for the leachate treatment, since for most criteria, it exhibits acceptable findings for the greater part of the criteria (mainly lower risk and cost effects) from the perspectives of all of the decision-makers. The other opposing alternatives show differences in ranking corresponding to different decision-makers. For example, the analysis results show that A4 is the worst ranked for the municipality decision-maker due to high economic cost and risk impacts in either the AHP or the PROMETHEE method. Furthermore, A1 shows the worst ranking in the case of the local community decision-maker, so A1 has a lower environmental performance or benefit for this decision-maker.

Conclusions

In this study, two MCDM (ANP and PROMETHEE) techniques were applied for ranking of leachate treatment alternatives. The ranking evaluation was carried out for three main clusters (benefit, cost and risk for the ANP and economic, environmental and technical for the PROMETHEE) and ten criteria. For the impact of the different perspectives in the decision-making system, experts from the municipality, landfill site, and local community were consulted. As a result of the study, both the ANP and PROMETHEE methods show that the combined treatment with municipal wastewater was determined as being the most appropriate option. This result demonstrates that the ANP and PROMETHEE are useful methods that can be applied to reach decisions between leachate treatment alternatives, since these methods consider expert views and decision-makers, such as the municipality as well as intangible criteria such as odor, in the evaluation. However, the ANP and the PROMETHEE methods have certain limitations. The ANP method is limited, as the maximum number of alternatives should be kept to less than seven to achieve consistency in the preferences (Senante-Molinos et al. 2015). The one limitation of the PROMETHEE method is the definition of the preference threshold values of the decision-makers in relation to the criteria considered. Another constraint is a computational limitation regarding the number of alternatives for the decision. In order to test the stability of the ranking of alternatives, firstly, two MCDM methods were performed, and secondly, a different sensitivity approach was considered with respect to the perspectives of three different decision-makers. Accordingly, high robust results are obtained. Although the ANP and PROMETHEE methods have a number of shortcomings, the advantages of these methods make them remarkable tools for modeling MCDM problems.

Various multi-criteria decision-making methods, such as VIKOR and ELECTRE, can be used for future studies, and analysis of the findings can be provided. Furthermore, a fuzzy decision-making environment may also be considered among the chosen models. Besides, a limitation of this study is the performance values obtained from partially secondary data. With regard to this limitation, this study can be expanded for primary data collection among real-scale facilities.

However, this study has a limitation that it relatively depends on the secondary data in the life cycle inventory phase.

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