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iTDAF IETI Transactions on Data Analysis and Forecasting

iTDAF | eISSN: 2959-0442 | Vol. 4 No. 2 (2026) | OPEN ACCESS

https://doi.org/10.3991/itdaf.v4i2.61713

PAPER

Assessment of Leachate Contamination Levels through LPI and Prioritization of Landfill Sites Using TOPSIS Method

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ABSTRACT

Leachate is the term used to describe the hazardous liquid substances that leak into the ground from municipal solid waste in a landfill. As a result, leachate contains many offensive substances from the material it has come through. The four main constituent types of leachates—dissolved organic substances, inorganic constituents, toxic metals, and xenobiotic organic pollutants—are the most dangerous by-products. The leachate volume and treatment cost are analyzed in this study using mathematical formulas. The rational method and the standard method are used to calculate the leachate generation rates, such as volume and amount. The Leachate Pollution Index, which is employed to evaluate the possibility of pollution from landfill leachate, is used in this study. Analysis was done on the landfill's leachate quality. For the Leachate Pollution Index, the following factors were taken into account: pH, Cl, Cr, Pb, Zn, Ni, Cu, and Fe. Okhla, Ghazipur, Hyderabad, Gurgaon, Kadapa, Narela-Bawana, and Ariyamangalam were the seven used landfills. The landfills are ranked using the Technique for Order Preference by Similarity to Ideal Solution method, which takes into account the leachate pollution index parameters, leachate generation rate, and leachate treatment cost. Ariyamangalam ranked first with a relative closeness value 1. Sensitivity analysis was carried out, showing consistent results without affecting the ranks. The findings demonstrate that a landfill site with a higher relative closeness performs better overall, with lower treatment costs, a lower generation rate, and a lower potential for pollution. For sustainable waste management techniques, locations with a higher relative closeness score are therefore more advantageous from an economic and environmental perspective.

KEYWORDS

Leachate Pollution Index, TOPSIS, leachate quality, rational method, standard method, leachate treatment cost

Ritha, W., Modenisha, U. (2026). Assessment of Leachate Contamination Levels through LPI and Prioritization of Landfill Sites Using TOPSIS Method. *IETI Transactions on Data Analysis and Forecasting (iTDAF)*, 4(2), pp. 65–74. https://doi.org/10.3991/itdaf.v4i2.61713

Article submitted 2026-03-26. Revision uploaded 2026-05-19. Final acceptance 2026-05-19.

1 INTRODUCTION

A conventional technique for getting rid of debris from mining operations, urban communities, and construction and demolition (C&D) sites is solid waste dumping. Dumping sites in India are found inside cities or a few kilometers outside. For instance, the Okhla dumping site is an open dumping site; the Ghazipur dumping site is unlined; and the Ariyamangalam, Trichy dumping site is an open dumping site. These dumping sites are typically non-engineered, unlined at the bottom and sideways, and lack a leachate collection system and top cover. These landfills normally contain mixed waste due to various waste generation sources [1].

Fluids passing through materials, substances, extracts, or soluble liquids, removing particulate matter and other contaminants from the environment, are called leachate. Further, in an aerobic environment, an extremely repulsive dark liquid known as leachate is created when solid waste is disposed [2], which in specific means the amount of toxic matter that is dissolved and circulated in environmental lands. Four primary pollutants are found in fluid leachate from the dumpsites, which is described as potent wastewater carrying a mixture of dissolved organic matter, heavy metals, xenobiotic organic compounds, and inorganic macro components. Leachate from the dump yards significantly contaminates both surface and groundwater, causing the most environmental threat.

On the basis of landfill age and the type of debris it consists of, the amount of variation in the composition of the landfill leachate can be determined [3]. Both suspended and dissolved materials are typically present in the leachate. The leachate is primarily produced by water precipitation seeping through landfill waste deposition. The percolating water becomes severely contaminated as soon as precipitation is exposed to the decomposed solid waste [4]. The carbonaceous materials in such solid waste break down, along with an intricate combination of various organic acids, alcohols, aldehydes, and simple sugars, to generate a range of other new substances, such as carbon dioxide and methane. In this regard, the risks of the produced leachate can be avoided and mitigated by the proper engineering design of landfill sites [5]. This involves constructing the landfill site on geologically impermeable substances and lining the landfill site with impermeable liners made of engineered clay or geomembrane materials. Such linings are required in most developed and a few developing countries, except where the solid waste is considered inert. Therefore, the majority of toxic, challenging, and hazardous materials should be left out of landfilling. However, it is frequently discovered that leachates from multiple locations contain a variety of hazardous contaminants as a result of illicit activity and, occasionally, lawful discarding of domestic or household goods. With this, a variety of pollutants are identified as evidence of legal or illegal residue disposal from residential items.

Leachate wastes, especially the freshest leachate, pose environmental risks due to their larger amount of organic pollutants, disease-causing microorganisms, and nitrogen-based compounds such as ammonia. However, relying on solid waste type, the presence of different concentrations of ammonia and other harmful pollutants is determined. Methane is typically produced in landfills by the presence of organic materials. Methane gas dissolves in the leachate in trace amounts. Areas of the leachate treatment plants with inadequate ventilation may release such methane gas into the atmosphere. The release of methane gas from these plants poses a risk of explosion and should be avoided. Leachate production is a vital environmental threat. The process of producing leachate from landfills in varying quantities and qualities is influenced by several factors. Several factors like the depth of the dump yard, amount of moisture content at the beginning, composition and density of waste, evaporation, runoff, and annual rainfall determine the quantity and quality of leachate production [6].

Groundwater and other water bodies can be severely contaminated by leachates, which are a variety of pollutants resulting from various types of landfilled waste. Therefore, the most important consideration in the operational and long-term oversight of municipal waste disposal facilities should be leachate monitoring. The diversity and variability of landfill leachate make it challenging to determine the true level of environmental threat and to choose the best disposal or treatment strategy. Thus, landfill management and operation must comprehend and measure the possibility of leachate contamination. Assessing the potential for leachate contamination could be used to gauge how accurately a landfill is operated or exploited and how it affects the surrounding areas [7].

Elevated levels of heavy metals and physicochemical contaminants have been found in studies on Indian landfill sites like Bhalswa, Okhla, and Ghazipur, suggesting serious pollution potential and ecological risks [8]. Significant groundwater contamination was further revealed by recent studies on the Ghazipur landfill, which also underlined the significance of efficient landfill management and spatial monitoring techniques [9]. The ecotoxicological and phytotoxic effects of untreated leachate have also been shown in extensive studies on landfill leachate characterization and toxicity assessment, highlighting the need for appropriate treatment and risk evaluation frameworks [10]. These results confirm the increasing demand for integrated assessment techniques for environmental management and landfill prioritization.

This studie's objectives are:

- To evaluate landfill leachate pollution using the leachate pollution index (LPI).
- To estimate leachate generation and treatment cost using standard and rational methods.
- To prioritize landfill sites using the TOPSIS framework.

Therefore, the current study incorporates LPI assessment, leachate generation estimation techniques, treatment cost evaluation, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)-based prioritization within a single framework, in contrast to earlier studies that independently assess landfill pollution or use Multi-Criteria Decision Making (MCDM) techniques only for ranking purposes. More sensible landfill management and decision-making are supported by this integrated approach.

2 MATHEMATICAL MODEL

2.1 Notations

V: Volume of leachate in m^3
T: Unit per leachate treatment cost
L_{TC}: Total leachate treatment cost
S: Volume of solid waste in tonnes.
V_L: Per year leachate discharge volume (m^3. year^{-1})
R: Annual rainfall (m)
A: Area of the landfill (m^2).
Q: Leachate production amount
I_j: Monthly precipitation (mm)
C: Coefficient of leachate generated

m: The number of leachate pollutant parameters for which data are available
w_i: The weight for the ith pollutant variable
p_i: The sub-index score of the ith pollutant variable
x_{ji}: Performance value of ith landfill under jth criterion
r_{ji}: Normalized value of ith landfill under jth criterion
v_{ij}: Weighted normalized value
w_j: Weight assigned to the jth criterion
A^+: Positive ideal solution
A^-: Negative ideal solution
v_j^+: Best value of the jth criterion
v_j^-: Worst value of the jth criterion
S_i^+: Distance from positive ideal solution
S_i^-: Distance from negative ideal solution
RC_i: Relative closeness coefficient of the ith landfill
a: Number of landfill alternatives
n: Number of evaluation criteria

2.2 Leachate Treatment Cost (LTC)

LTC is determined using the following formula. The volume (m^3) of Equation (2) of leachate (V) multiplied by the treatment price (T) is used to estimate the costs.

$$L_{TC} = \sum V \times T \tag{1}$$

2.3 The Leachate Volume for LTC

To identify the leachate production volumes in dumpyards, Equation 2 is employed. When a tonne (t) of solid debris (S) is multiplied by 0.21 cubic meters (m^3t^{-1}) [8].

$$V = \sum S \times 0.21 \tag{2}$$

2.4 Standard method

Many nations around the world have adopted the standard method. This mathematical model is used to find the amount of leachate produced from municipal solid waste (MSW). Since it is straightforward and has been in use for a long time, this is one of the most popular methods to determine the leachate generated in municipal dump yards.

$$V_L = 0.15 \times R \times A \tag{3}$$

2.5 Rational method

The rational method calculates the amount of leachate produced by taking into account specific parameters. The leachate generation coefficient, landfill area, and rainfall precipitation are the parameters. When determining the coefficient, the type of landfill that is, whether it is an old landfill, that has been closed or one that is currently in use, is taken into account. The coefficient taken into consideration is 0.3 for an old dumpsite and 0.5 for a landfill that is currently in use [11].

$$Q = I_j \times C \times A \tag{4}$$

2.6 LPI

The LPI was created to evaluate the potential for leachate pollutants at landfill locations. Using this approach, a single value determined by the equation represents the overall leachate quality rating. When the number of leachate pollutant variables is less than 18, then the modified Equation (5) is used [12].

$$LPI = \frac{\sum_{i=1}^{m} w_i p_i}{\sum_{i=1}^{m} w_i} \tag{5}$$

2.7 TOPSIS method

The chosen landfill sites were ranked using a variety of operational and environmental factors using the TOPSIS. The LPI, leachate generation estimated using the standard method, leachate generation estimated using the rational method, and LTC were among the criteria taken into consideration in this study. Normalization was used to remove dimensional inconsistencies and create a normalized decision matrix because the chosen criteria had different units and magnitudes. To reduce subjective bias and guarantee a balanced contribution among the chosen indicators, equal weighting was used for all criteria. The positive and negative ideal solutions were subsequently determined using the weighted normalized matrix. To rank the landfill locations, the relative closeness (RC) coefficient and Euclidean distances from the optimal solutions were computed. According to the suggested framework, landfill locations with higher closeness coefficient values were deemed environmentally preferable [13].

Normalization.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{a} x_{ij}^2}} \tag{6}$$

Weighted normalized matrix.

$$\mathrm{v_{ij} = w_{ij} r_{ij}} \tag{7}$$

Ideal solutions.

$$\begin{aligned} A^+ &= \{v_1^+, v_2^+, \cdots, v_n^+\} \\ A^- &= \{v_1^-, v_2^-, \cdots, v_n^-\} \end{aligned} \tag{8}$$

Separation distance.

$$\begin{aligned} S_i^+ &= \sqrt{\sum (v_{ij} - v_j^+)^2} \\ S_i^- &= \sqrt{\sum (v_{ij} - v_j^-)^2} \end{aligned} \tag{9}$$

RC coefficient.

$$RC_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{10}$$

3 PROBLEM DESCRIPTION

In India, evaluating landfills requires a multifaceted approach that combines strict monitoring and management practices with site suitability analysis. MCDM is frequently used in site selection to take into account environmental, social, and economic factors. Environmental compliance during operation depends on leachate management, waste weighing, sampling, and recordkeeping. Seven landfill sites across India were chosen based on the availability, consistency, and comparability of physicochemical leachate parameters from literature. The sites are ranked using the MCDM method TOPSIS, taking into account the volume and amount of leachate along with LPI using a number of parameters. Since the TOPSIS method produced better results for landfill selection in earlier studies, this approach is primarily used. The parameters and values for LPI estimation of the seven landfills taken into consideration for this study are shown in Table 1 [14, 15]. Table 2 consists of the input values for leachate calculations, and Table 3 shows sensitivity analysis weight values. The data of total solid waste generated, annual rainfall, monthly rainfall for the peak monsoon month of July, and area of landfill for each landfill site were collected from publicly available online sources, including meteorological and municipal websites [16–20].

Table 1. Parameters and landfills for LPI

Parameters	Gurgaon Dumping Site	Hyderabad Dumping Site	Kadapa Dumping Site	Okhla Dumping Site	Ghazipur Dumping Site	Narela-Bawana Dumping Site	Ariyamangalam Dumping Site
pH	6.62 ± 0.08	7.42 ± 0.12	7.29 ± 0.04	7.56 ± 0.06	8.25 ± 0.09	9.41 ± 0.22	8.06 ± 0.10
Chloride (mg/L)	7166.67 ± 351.26	9169.34 ± 377.52	1644.55 ± 78.45	11,948.67 ± 852.35	6520.45 ± 96.57	7206.34 ± 21.23	184.7 ± 55.4
Sulfate (mg/L)	1353.34 ± 83.27	692.67 ± 30.36	135.25 ± 7.05	1157.67 ± 100.52	361.34 ± 42.16	501.67 ± 22.55	369.7 ± 42.8
Fe (mg/L)	26.38 ± 5.29	13.24 ± 2.75	12.18 ± 2.42	43.67 ± 2.80	49.45 ± 3.03	36.26 ± 2.09	0.006 ± 0.62
Zn (mg/L)	7.28 ± 1.04	4.22 ± 0.96	1.04 ± 0.07	3.09 ± 0.39	2.34 ± 0.38	6.98 ± 0.12	0.562 ± 0.005
Cu (mg/L)	0 ± 0	0.35 ± 0.09	0.19 ± 0.01	0.32 ± 0.02	1.58 ± 0.07	0.95 ± 0.14	0.041 ± 0.001
Cr (mg/L)	4.56 ± 1.48	0.32 ± 0.03	0.35 ± 0.29	1.34 ± 0.12	0.97 ± 0.37	2.15 ± 0.07	0.162 ± 0.003
Pb (mg/L)	2.44 ± 0.87	0.46 ± 0.09	0.41 ± 0.05	0.34 ± 0.08	1.56 ± 0.54	1.52 ± 0.18	0.010 ± 0.001
Ni (mg/L)	0 ± 0	1.02 ± 0.31	0 ± 0	0.55 ± 0.13	2.36 ± 0.79	0 ± 0	0.089 ± 0.005

Table 2. Input data for calculating LTC, standard method and rational method

Site	Total SW (Tonnes)	Annual Rainfall (mm)	Area of Landfill (acers)	Monthly Rainfall (mm)
Okhla	6000000	706	40	180
Ghazipur	15000000	900	56	338
Narela-Bawana	2,62,80,000	13.04	100	180
Gurgaon	1,31,40,000	596	350	196
Kadapa	200000	782.88	10	100
Hyderabad	2,97,84,950	810	10	180

Table 3. Sensitivity weight scenarios

Scenario	LPI	Standard Method	Rational Method	LTC
Base case	0.25	0.25	0.25	0.25
Scenario 1	0.35	0.22	0.22	0.21

4 RESULT AND DISCUSSION

The first step is to estimate the cost of leachate treatment using Equation 1, and then to estimate the volume and amount of leachate using the standard and rational methods. The estimation of leachate generation was based on the landfill's total area and annual rainfall data, while the estimation of treatment costs was based on the total solid waste in tonnes. The values in Table 1 were used to estimate LPI. After obtaining all of the results, the landfill sites were ranked according to the relative closeness coefficient values, which were determined using the TOPSIS method with all of these factors as input parameters. The following Table 4 and Figure 1 show the ranking of landfills; Ariyamangalam ranked 1, as it showed comparatively lower LPI values, lower estimated leachate generation, and lower treatment cost, which indicates less environmental burden than the other landfill sites. Narela-Bawana and Ghazipur were ranked lower with an RC value of 0.141 and 0.003 because of higher concentrations of contaminants, higher estimates of leachate generation, and higher treatment cost requirements. Therefore, they need higher importance, and treatment can reduce leachate treatment. It is clear that an RC value closer to 1 is very close to ideal and best and identifies the better landfill site according to the given criteria. Python code was implemented to obtain the LPI and TOPSIS results. The current results are consistent with recent MCDM landfill assessment studies, which found that landfill sites with lower environmental risk, lower operational impacts, and lower contaminant burden generally performed better when ranked using TOPSIS-based evaluation frameworks.

Table 4. Sensitivity analysis results

Landfill	Base Rank	Scenario 1 Rank
Ariyamangalam	1	1
Kadapa	2	2
Gurgaon	3	3
Hyderabad	4	4
Okhla	5	5
Narela-Bawana	6	6
Ghazipur	7	7

In order to assess ranking robustness under different weighting conditions and to enhance methodological reliability, sensitivity analysis has been widely recommended in recent TOPSIS and MCDM studies. A sensitivity analysis was conducted by slightly adjusting the weights of the TOPSIS criteria in this study. The suggested integrated LPI–TOPSIS framework is comparatively stable and insensitive to moderate weight variation, as evidenced by the ranking order remaining unchanged under the modified weighting scenario.

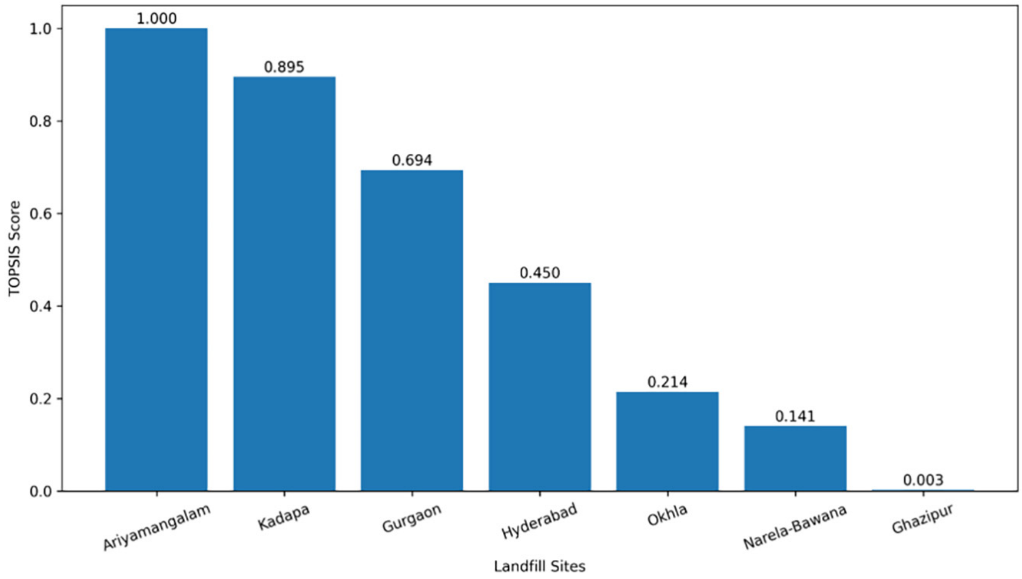

Fig. 1. TOPSIS relative closeness ranking of landfill sites

5 CONCLUSION

Utilizing sustainable landfill management techniques, like recycling, cutting back on waste production, and applying the concepts of the circular economy, can reduce the need for landfills and the quantity of leachate generated. In order to safeguard the ecological and human health in India from the detrimental effects of landfill debris, efficient leachate treatment and landfill management are essential. Based on LTC, leachate generation rate, and LPI, the TOPSIS method's estimated results for the landfill sites showed that lower RC values with lower landfill ranks necessitate treating the sites with more care and handling, which raises the cost and pollution of leachate generation. Additionally, landfills with higher RC values are more desirable because they have lower environmental burden, optimized treatment costs, and less leachate pollution. This method helps decision-makers prioritize landfill management strategies and enables a thorough ranking. The study is limited by incomplete landfill monitoring datasets, seasonal and geographical variations in leachate characteristics, and oversimplified assumptions used in leachate generation estimation techniques. However, in situations where data is limited, the integrated framework offers a useful comparative method for landfill prioritization.

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