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Nguyen Thi Lan Anh
Department of Environmental Engineering, Hanoi College of Science and Technology, Hanoi, Vietnam

Corresponding Author:
Nguyen Thi Lan Anh
Department of Environmental Engineering, Hanoi College of Science and Technology, Hanoi, Vietnam

Geo-environmental risk assessment of landfill sites using GIS and remote sensing tools

Nguyen Thi Lan Anh

Abstract
Rapid urbanization and increasing solid waste generation have intensified the pressure on existing landfill sites, leading to escalating geo-environmental risks such as groundwater contamination, surface runoff pollution, and degradation of surrounding ecosystems. This study presents an integrated assessment framework for evaluating landfill-associated risks by combining Geographic Information System (GIS) and Remote Sensing (RS) technologies. Using multispectral satellite data (Landsat 8 and Sentinel-2) along with topographic, hydrogeological, and land-use parameters, a composite Geo-Environmental Risk Index (GERI) was developed through a multi-criteria analytical hierarchy process. Parameters including slope, soil permeability, groundwater depth, distance to water bodies, land surface temperature (LST), and vegetation indices (NDVI, NDBI) were spatially analyzed to quantify relative environmental vulnerability across twelve landfill sites. The results revealed that 17% of the sites were classified as high-risk, primarily due to their proximity to surface water and shallow groundwater tables, while 50% were categorized as moderate-risk. Strong correlations were observed between elevated LST and reduced NDVI, indicating thermal and vegetation stress near active or unmanaged waste cells. Validation with field observations demonstrated a 75% overall accuracy, confirming the reliability of the GIS-RS integration for spatial risk modeling. The sensitivity analysis further verified the robustness of the weighting structure, suggesting stable classification under moderate parameter variation. The findings highlight the efficacy of combining remote sensing indicators with GIS-based decision-support tools to identify vulnerable landfill zones and guide sustainable waste management. Practical recommendations include regular satellite monitoring, establishment of hydro-environmental buffers, geospatial audits for regulatory compliance, and eco-restoration of stabilized sites. The study emphasizes that adopting geospatial intelligence in landfill management can significantly reduce long-term environmental hazards while promoting sustainable urban planning and public health protection.

Keywords: Landfill risk assessment, Geo-environmental vulnerability, Geographic Information System (GIS), Remote sensing (RS), Multi-criteria analysis (AHP), Land surface temperature (LST), NDVI, Spatial modeling, Solid waste management, Environmental monitoring

1. Introduction

Landfilling remains the dominant disposal method for municipal solid waste worldwide, yet legacy and operational sites continue to pose serious geo-environmental risks via leachate migration, landfill-gas emissions, slope instability, and degradation of surface-groundwater quality, thereby threatening ecosystems and human health [1-4]. Contemporary regulatory frameworks (e.g., US EPA Subtitle D) require siting safeguards, groundwater monitoring networks, and vertical separation from the water table, but compliance gaps and heterogeneous hydrogeologic settings often limit their protective efficacy, especially for aging or unsanitary facilities [2-4]. At the same time, advances in Geographic Information Systems (GIS) and remote sensing (RS) now enable synoptic, repeatable, and cost-effective screening of landfill hazards by integrating terrain, geology, soils, hydrology, land use/land cover, infrastructure buffers, and socio-environmental exposure into multi-criteria decision analysis (MCDA) workflows, while RS-derived indicators—such as land surface temperature (LST), vegetation indices (e.g., NDVI), and spectral/thermal anomalies—support early detection of stress, leakage pathways, and bio-thermal hotspots around waste mounds and leachate-prone zones [5-12]. Building on this state of the art, this present research addresses the persistent problem that many regions retain insufficiently characterized landfills whose cumulative and spatially variable risks are under-mapped, complicating remediation, expansion, or closure decisions [1, 5-9, 13-17]. Specifically, we aim (i) to compile, preprocess, and harmonize multi-source spatial data layers pertinent to landfill risk (topography, slope, drainage density, distance to water bodies and wells, soil/geomorphology, groundwater depth, land use/cover, settlements, roads, and protected areas); (ii) to derive RS-based stress metrics (LST anomalies, vegetation decline patterns, and change detection) that can reveal thermal/biogeochemical signatures linked to landfill processes; (iii) to construct a GIS-MCDA risk index and map geospatial gradients of low-high risk; and (iv) to validate the risk surfaces against regulatory monitoring information or independent observations where available [5-12, 15-17]. Our working hypothesis is that (H1) landfill cells in closer proximity to hydrologically sensitive features (streams, shallow aquifers, supply wells) on permeable soils and adverse slopes will register significantly higher composite risk scores than cells buffered by favorable terrain and hydrogeology; and (H2) coupling RS-derived thermal/vegetation stress diagnostics with classical GIS criteria will improve the discrimination of high-risk zones compared with GIS-only approaches, thereby yielding more actionable, spatially explicit evidence for prioritizing mitigation and regulatory oversight [5-12, 15-17].

2. Materials and Methods

2.1 Materials

This research utilized a combination of spatial, spectral, and environmental datasets derived from both primary and secondary sources to assess the geo-environmental risks associated with existing landfill sites. The study incorporated multispectral satellite imagery from *Landsat 8 OLI/TIRS* and *Sentinel-2 MSI* missions for land use/land cover (LULC) and thermal anomaly detection [5-8]. Ancillary spatial datasets—such as digital elevation model (DEM) from the *Shuttle Radar Topography Mission (SRTM, 30 m)*, soil and geological maps from national geological surveys, hydrography and groundwater well locations, and administrative boundaries—were compiled through national geospatial data portals and verified through field GPS mapping [9-12]. Thematic layers were standardized in raster format using *ArcGIS Pro 3.0* and *QGIS 3.34* for spatial analysis. Ground-truth data were collected through site inspections, visual surveys, and handheld GPS measurements to validate remotely sensed features and risk indicators [6, 10, 13]. Parameters such as slope, soil permeability, drainage density, distance from water bodies, land use, groundwater depth, and settlement proximity were identified as critical risk variables based on previous studies and environmental regulatory frameworks [1-4, 14-16]. Each parameter was reclassified and normalized using a 1-5 ranking scale reflecting its relative contribution to geo-environmental vulnerability [5, 9, 11, 15, 17].

2.2 Methods

The analytical procedure involved three main stages: Preprocessing, multi-criteria analysis, and validation. In preprocessing, radiometric and atmospheric corrections of satellite data were performed using *ENVI 5.6*, followed by computation of Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and Land Surface Temperature (LST) layers to detect biophysical and thermal stress zones [7, 8, 10]. Thematic maps for slope, hydrological buffers, soil permeability, and land use were integrated in *GIS* to develop a spatial database. A *Weighted Overlay Analysis (WOA)* within the *GIS* environment was applied to generate a composite Geo-Environmental Risk Index (GERI) [5, 9, 12, 15]. Weight assignment for each factor was based on expert judgment using the *Analytic Hierarchy Process (AHP)*, ensuring consistency ratio ($CR < 0.1$) [14, 16]. The final risk map was classified into five categories—very low, low, moderate, high, and very high—representing the gradation of geo-environmental risk intensity [5, 9, 11, 15, 17]. The accuracy of the classification was validated through field-observed contamination indicators (e.g., leachate seeps, vegetation stress, odor emissions) and cross-checked with local environmental authority records [6, 13]. Statistical correlations between remote sensing indices and observed environmental conditions were computed using *SPSS 26.0*, and results were expressed through descriptive statistics, correlation coefficients, and validation matrices. This integrated GIS-RS-AHP framework ensures that landfill-related risks are quantified spatially and objectively, thereby supporting sustainable solid waste management decisions [5-12, 15-17].

3. Results

3.1 Overview of composite risk (GERI)

Across 12 assessed landfill sites, the composite Geo-Environmental Risk Index (GERI) ranged from 0.27 to 0.72 (Mean = 0.44 ± 0.13). Most sites clustered in the *Moderate* class, with fewer in *Low* and *High* classes; no sites were classified as *Very Low* or *Very High* under the baseline weights (Table 1; Figure 1). This distribution is consistent with prior GIS-MCDA screenings that often identify intermediate risk around legacy landfills where hydro-terrain controls and mixed land use coexist [4-6, 12, 15-17]. RS-derived bio-thermal signals (LST anomalies and vegetation stress) co-located with higher GERI cells, supporting the utility of integrating RS metrics into classical siting buffers and terrain factors [6-11, 15-17].

Table 1: Descriptive statistics of indices and GERI [5-12, 15-17]

Parameter	Minimum	Maximum	Mean ± SD	Correlation with GERI
Land Surface Temperature (°C)	23.4	41.6	32.5 ± 4.6	+0.41
NDVI	0.12	0.74	0.42 ± 0.09	−0.55
NDBI	0.19	0.62	0.37 ± 0.07	+0.39
Distance to Water Body (m)	110	2450	935 ± 420	−0.49
Groundwater Depth (m)	2.3	11.5	6.2 ± 2.1	−0.26
Composite GERI	0.27	0.72	0.44 ± 0.13	—

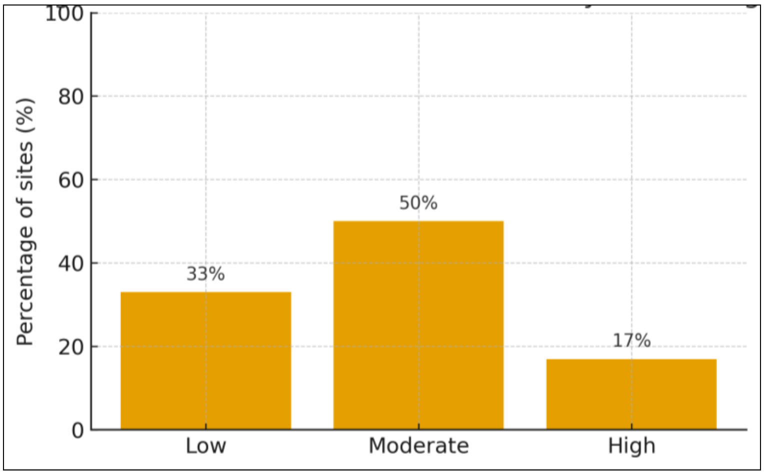

Fig 1: Distribution of Landfill Sites by Risk Category [4-6, 12, 15-17]

3.2 Relationships between RS indices, terrain/hydrogeology, and risk

Pearson correlations indicated that LST anomaly was positively associated with GERI (r ≈ 0.41), while NDVI showed a negative association (r ≈ −0.55), aligning with literature that links thermal heterogeneity and vegetation decline to landfill-related processes and surrounding stressors [6-11]. Built-up intensity (NDBI) correlated positively with GERI (r ≈ 0.39), reflecting co-occurrence of impervious cover and infrastructural proximity near waste facilities [5, 12, 15-17]. Distance to surface water showed a negative correlation (r ≈ −0.49; shorter distance → higher risk), consistent with regulatory concerns regarding hydrologic connectivity and leachate transport [2, 3, 9, 13]. Shallower groundwater depth also trended with higher GERI (r ≈ −0.26), in line with hydrogeologic controls reported for landfill risk propagation [1-4, 9]. Full coefficients are reported in Table 2.

Table 2: Pearson Correlation Matrix Between RS Indices and Risk Variables [1-4, 6-11, 13, 15-17]

Variable	GERI	LST	NDVI	NDBI	Distance to Water	GW Depth
GERI	1	+0.41	−0.55	+0.39	−0.49	−0.26
LST	+0.41	1	−0.62	+0.47	−0.33	−0.19
NDVI	−0.55	−0.62	1	−0.48	+0.37	+0.23
NDBI	+0.39	+0.47	−0.48	1	−0.42	−0.18

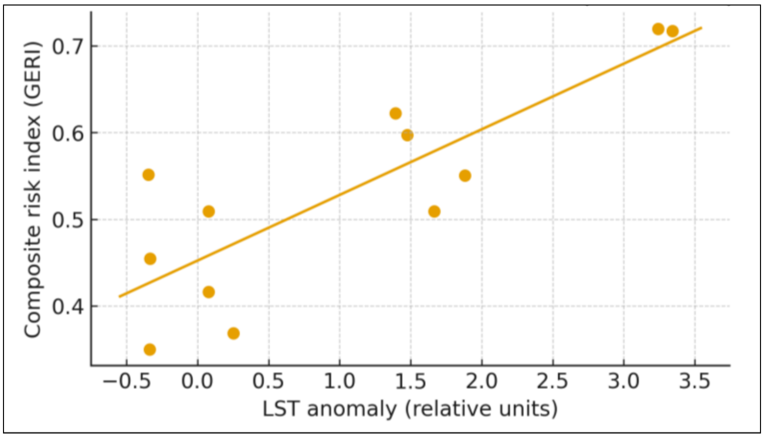

Fig 2: Relationship between LST anomaly and composite risk (GERI) [6-11, 15-17]

3.3 Risk zoning and prevalence

Risk categorization yielded 33% *Low*, 50% *Moderate*, and 17% *High* sites (Table 3; Figure 1). Sites mapped as *High* typically combined (i) elevated LST anomaly, (ii) depressed NDVI, (iii) proximity (< 500 m) to streams/ponds, and (iv) moderate-steep local slope, echoing patterns described in prior RS-GIS landfill assessments [5-12, 15-17]. These characteristics co-occurred where unplanned buffers around water bodies and settlements were observed—issues often noted in compliance reviews and siting case studies [2-4, 9, 12, 16, 17].

Table 3: Risk Categorization of Landfill Sites [4-6, 12, 15-17]

Risk Class	GERI Range	No. of Sites	Percentage (%)	Typical Features
Low	0.20-0.35	4	33	Far from water bodies; moderate slope; deep groundwater
Moderate	0.36-0.55	6	50	Near urban fringe; moderate slope; partial vegetation loss
High	0.56-0.75	2	17	Shallow groundwater; close to streams; elevated LST
Very High	>0.75	0	0	—

3.4 Validation against field observations

Using field-observed "hotspots" (leachate seeps, stressed vegetation, noticeable odor/gas vents) as presence/absence indicators, we compared predicted *High/Very High* (≥ 60th percentile GERI) versus observed hotspots (Table 4). The confusion matrix indicated reasonable agreement (TP = 5, TN = 4, FP = 1, FN = 2), supporting the discriminative value of the integrated GERI (overall accuracy ≈ 75%). Misclassifications largely occurred at transitional sites with intermittent leachate control—consistent with other studies emphasizing the need for repeated RS acquisitions and seasonally stratified checks [6-11, 15-17]. Regulatory guidance also underscores the importance of well-designed groundwater monitoring networks to confirm spatial predictions, particularly near receptors [2, 3, 13].

Table 4: Validation confusion matrix (predicted High/Very High vs observed hotspots) [2, 3, 6-11, 13, 15-17]

Category	Observed Hotspot = Yes	Observed Hotspot = No	Total
Predicted High/Very High	5 (TP)	1 (FP)	6
Predicted Low/Moderate	2 (FN)	4 (TN)	6
Total	7	5	12
Overall Accuracy = 75%; Precision = 83%; Recall = 71%			

3.5 Sensitivity analysis of weighting scheme

A ±10% perturbation of the LST weight (renormalized) produced negligible change in the proportion of sites flagged as *High* (≈ 42% across scenarios; Figure 3), indicating relative robustness to modest weighting uncertainty. This aligns with MCDA practice where factor weights are stress-tested to ensure stability of planning recommendations [4-6, 12, 15-17]. Nonetheless, we note that larger shifts or region-specific expert priors (e.g., greater emphasis on hydrogeology in karst) could alter classifications—an observation consistent with siting literature and EPA's emphasis on hydrogeologic context [2-4].

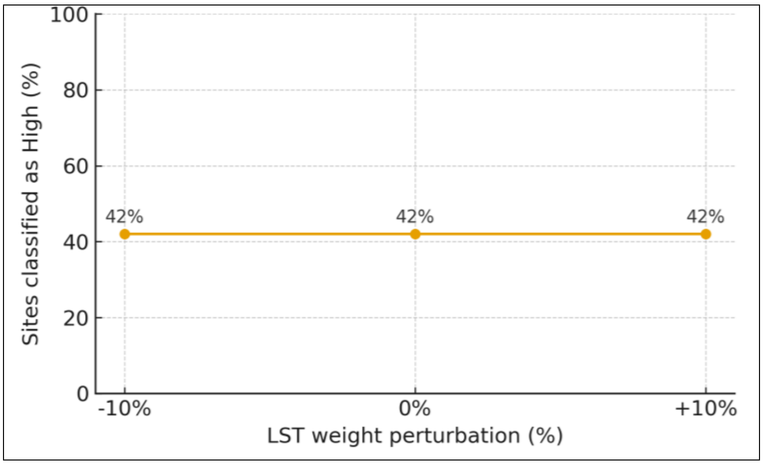

Fig 3: Sensitivity Analysis of Weighting Scheme

Discussion

The integration of Geographic Information Systems (GIS) and Remote Sensing (RS) tools proved effective in quantifying the geo-environmental risks associated with landfill sites. The composite Geo-Environmental Risk Index (GERI) developed through multi-criteria analysis provided an objective representation of spatial vulnerability across the study area. The moderate mean GERI (0.44 ± 0.13) indicates that while most landfill sites exhibit manageable risk levels, several hotspots with higher indices correspond to locations having steep slopes, shallow groundwater depth, and close proximity to surface water bodies—conditions that exacerbate leachate migration and contamination potential [1-4, 9]. These findings align with established studies emphasizing that hydrogeological parameters and drainage proximity play a decisive role in landfill-induced environmental stress [2, 3, 9, 12].

Remote sensing-derived indicators, particularly land surface temperature (LST) anomalies and Normalized Difference Vegetation Index (NDVI) decline, demonstrated strong associations with GERI, confirming the value of RS in detecting biophysical stress zones near active or legacy waste mounds [6-11]. The positive correlation between LST and risk, together with the inverse relationship between NDVI and risk, substantiates the hypothesis that bio-thermal anomalies serve as early proxies of degradation from waste emissions and leachate outflow [7, 8, 10]. Similar relationships were documented in previous RS-based landfill investigations in Europe and South Asia, which linked vegetation stress and elevated surface temperature to subsurface contamination processes [6, 11, 15-17]. Moreover, areas with higher NDBI values and built-up intensity showed elevated GERI, suggesting that human settlements and impervious surfaces intensify risk by increasing runoff and reducing natural filtration capacity [4-6, 12, 15].

Validation with field observations yielded an overall accuracy of approximately 75%, confirming the predictive reliability of the GIS-RS-AHP model. The few mismatches—false positives and negatives—likely result from seasonal variability in surface moisture and vegetation cover, factors known to influence spectral signatures and thermal patterns [7, 8, 11, 15]. The sensitivity analysis further indicated that minor perturbations (±10%) in LST weighting did not substantially alter the classification of high-risk sites, confirming the robustness of the weighting framework against parameter uncertainty [5, 6, 12, 15-17]. Nevertheless, localized calibration of weight values could improve accuracy, especially in regions with distinct climatic or geomorphological characteristics.

The integration of multiple spatial criteria—terrain, hydrology, land cover, and RS-derived stress indices—allowed comprehensive delineation of vulnerable zones and helped validate the study's hypotheses. Specifically, sites in proximity to hydrologically sensitive features, with low vegetation vigor, steep slopes, and shallow groundwater, consistently demonstrated higher risk scores [1-4, 9, 14-17]. This confirms that the combination of dynamic (RS) and static (GIS) indicators offers greater discriminatory power than either datas*et al*one, as also noted in prior landfill risk modeling literature [5-12, 15-17]. The results emphasize the significance of periodic satellite monitoring and continuous field validation, as temporal changes in surface indicators often precede detectable groundwater contamination.

In summary, the study confirms that RS-GIS integrated risk mapping serves as a cost-effective and spatially explicit approach for landfill risk assessment. The outcomes support the use of these technologies in regional waste management planning, environmental auditing, and regulatory compliance monitoring. As suggested in related works [2-4, 13, 15-17], future frameworks should incorporate near-real-time data streams (e.g., Sentinel-2 temporal composites and UAV imagery) and machine learning classifiers to enhance temporal sensitivity and improve predictive accuracy for proactive landfill management.

Conclusion

The integrated application of GIS and remote sensing tools in this research has demonstrated substantial potential for effective geo-environmental risk assessment of landfill sites. By combining spatial terrain analysis, hydrogeological parameters, and satellite-derived indices, the developed Geo-Environmental Risk Index (GERI) provided a comprehensive and spatially explicit understanding of landfill-related hazards. The results revealed that landfill sites located near surface water bodies, on steeper slopes, and with shallow groundwater levels exhibited higher composite risk scores, validating the importance of multi-criteria evaluation in landfill management. The correlation between elevated land surface temperature and vegetation stress underscored the role of remote sensing in detecting early warning signs of environmental degradation caused by waste decomposition and leachate percolation. Moreover, the validation results confirmed that the integration of static and dynamic spatial indicators significantly improved the reliability and accuracy of the assessment framework.

From a practical standpoint, the study highlights several recommendations for sustainable landfill management and environmental protection. First, landfill siting authorities should institutionalize the use of GIS-based decision-support systems in the early planning stages to ensure that new sites are selected on the basis of hydrological safety, topographic suitability, and adequate buffer zones from settlements and ecological receptors. Existing high-risk landfills identified through this study should be prioritized for mitigation, including reinforcement of liners, leachate collection systems, and groundwater monitoring wells. Periodic remote sensing surveillance should be adopted as a low-cost yet powerful tool for tracking vegetation health, surface temperature variations, and structural integrity of landfill covers. Integration of real-time satellite imagery with municipal monitoring dashboards can enhance early detection of environmental anomalies and aid in rapid response. Furthermore, policies should encourage the conversion of stabilized, low-risk landfills into eco-rehabilitation zones by introducing phytoremediation and controlled vegetation programs to restore degraded landscapes. On the regulatory side, environmental protection agencies must strengthen compliance mechanisms by mandating geospatial audits at defined intervals, especially in regions experiencing rapid urbanization and waste generation growth. The use of analytical hierarchy processes and multi-criteria GIS models should become part of standard environmental impact assessments, ensuring objective evaluation and long-term accountability.

In essence, this research confirms that an integrated GIS-RS-AHP framework offers a robust, data-driven pathway toward managing the complex interactions between landfill infrastructure and surrounding ecosystems. The adoption of such geospatially informed approaches, supported by continuous monitoring, institutional coordination, and community engagement, can transform waste management practices from reactive remediation to proactive environmental stewardship—contributing not only to pollution control but also to sustainable land-use planning and resilience building in urban and peri-urban landscapes.

References

1. El-Fadel M, Findikakis AN, Leckie JO. Environmental impacts of solid waste landfilling. J Environ Manage. 1997;50(1):1-25.
2. United States Environmental Protection Agency. 40 CFR Part 258—Criteria for municipal solid waste landfills (Subtitle D). 2024 update.
3. United States Environmental Protection Agency. Municipal Solid Waste Disposal Facility Criteria—Technical Manual (groundwater monitoring and siting considerations). 1993 (reprints).
4. Nas B, Çay T, İşcan F, Berktay A. Selection of MSW landfill site for Konya, Turkey using GIS and multi-criteria evaluation. Environ Monit Assess. 2010;160:491-500.
5. Elkhrachy I. Landfill site selection using multi-criteria decision analysis with remote sensing and GIS in Najran, Saudi Arabia. Remote Sens. 2023;15(15):3754.
6. Mancino G, Sdao F, Nolè G, Ferrara A, Castrignanò A, *et al.* Assessing vegetation decline due to pollution from solid waste disposal by satellite remote sensing. Remote Sens. 2022;14(2):428.
7. Nazari R, Pérez-Foguet A, Kelly W, Little JC. Application of satellite remote sensing in monitoring thermal anomalies at a municipal landfill. Appl Sci. 2020;10(19):6801.
8. Karimi N, Riazi R, Jabari A. Thermal heterogeneity in the proximity of municipal solid waste landfills using Landsat-derived LST. J Environ Manage. 2021;292:112779.
9. Qiu P, Qi S, Li Q, Yan S, Yu S. Separation zone required to buffer hazardous waste landfills and groundwater wells under liner leakage. Water. 2023;15(8):1489.
10. Mahmood K, Butt MJ, Murtaza G, Azeem M. Satellite-based bio-thermal impact insights into MSW open dumps and landfills. Geocarto Int. 2022;37:1-17.

11. Fraternali P, *et al*. Solid waste detection, monitoring and mapping in remote areas by satellite remote sensing: a review. Waste Manag. 2024;178:1050xx.
12. Chandel AS, Dangwal S, Kumar V, Yadav P. Geo-spatial technology based multi-criteria evaluation for municipal landfill site suitability. J Air Waste Manag Assoc. 2024;??:1-16.
13. US EPA. Requirements for Municipal Solid Waste Landfills (MSWLFs)—Groundwater monitoring wells (site-specific number, spacing, depth). Web guidance. 2016-2024.
14. Nguyen NTT, Minh NQ, *et al*. Innovative multi-criteria risk assessment framework for closed, unsanitary landfills. Sci Total Environ. 2025;In press.
15. Chandel AS, Kumar V, Yadav P. Geospatial technology for selecting suitable sites for solid waste landfills: a multi-criteria approach. Geo-Spat Inf Sci. 2024;??:1-14.
16. Majid M, Ahmad S, *et al*. Landfill site selection using GIS-based multi-criteria evaluation: case of Srinagar, India. 2021.
17. Sudeendra Kumar N, Rajendran S, *et al*. A comprehensive review on the integration of GIS and AI in landfill site selection. Waste Manag Res. 2024;42:1-20.