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INTEGRATED GIS-BASED GEOTECHNICAL AND MULTI-CRITERIA EVALUATION FOR LANDFILL SITING: IMPLICATIONS FOR URBAN GROUNDWATER AND PUBLIC HEALTH PROTECTION

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ABSTRACT

Waste mismanagement is a serious challenge in Nigeria, where the lack of sanitary landfills is escalating environmental degradation and groundwater-related health threats. Some of the existing dumpsites in the metropolitan areas have been overtaken by rapid urbanization and industrialization, thereby necessitating new landfill sites appropriate for today's urban setting. Landfills have proven to be sustainable solutions for municipal solid waste management worldwide. However, their effectiveness depends on proper siting which considers prevailing geo-environmental and geospatial conditions for hydrogeological and ecological benefits. This study integrates geotechnical characterization with GIS-based multi-criteria analysis to delineate suitable landfill sites in Ado-Odo/Ota and environs, southwestern Nigeria. The Analytical Hierarchy Process (AHP) was employed to compute a pair-wise comparison matrix to assign appropriate weights to six spatial suitability criteria, namely, depth to water table, land use/land cover, soil, slope, distance from lineaments, and road proximity. The criteria were then integrated using a GIS-based weighted overlay technique to generate a site suitability map. Geotechnical results for the amount of fines (25.7-35.9%), maximum dry density (1690 - 1897 kg/m³), plasticity index (8.3 -18.3%), and permeability (2.23 × 10-4 to 1.04 × 10-3 m/s) indicate positive containment potential. The resulting suitability map classified 12.17 km² (1.41%) as very suitable, 775.56 km² (89.96%) as moderately suitable, and 74.34 km² (8.62%) as unsuitable. The receiver operating characteristic (ROC) analysis for model validation gave an Area Under the Curve (AUC) of 0.816, suggesting strong and reliable suitability prediction. This study delineated four potential sites for sustainable landfills that could guide urban planners and policy makers towards safeguarding urban groundwater, reducing public health risks, and informing rational waste management planning in the rapidly urbanizing and industrializing corridor.

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INTRODUCTION

Environmental and public-health challenges arising from waste mismanagement, which is often worsened by population explosion, increasing urbanization, and accompanying huge municipal solid waste (MSW) generation, have raised much concern globally (Degefu and Asefa, 2024; Purohit et al., 2026).The situation in low- and middle-income developing sub-Saharan countries is more threatening because scarcity of waste management infrastructure is commonplace (Asefa et al., 2021; Ayodele et al., 2026; Maalouf and Agamuthu, 2023; Wuave, 2024). Sanitary landfills, when well designed and properly sited, have proven to offer sustainable and effective solutions for mitigating environmental degradation, such as controlling leachate and gaseous emissions that threaten surface water, groundwater resources, and human health. Therefore, the protective performance of landfills is a function of both engineered controls and appropriate site selection, which help to minimize hydrogeological vulnerability and exposure pathways (Degefu and Asefa, 2024; Owoseni, 2023).

Groundwater contamination with inorganic and organic pollutants, heavy metals, and other potentially toxic elements, posing direct and indirect risks to drinking-water supplies and ecosystems, has been associated with leachate migration from poorly located or improperly lined waste facilities (Wuave, 2024). Open dumps and informal disposal sites commonly co-exist with shallow unconfined aquifers in most parts of Nigeria and other fast urbanizing West African settings. This menace often heightens the potential for contaminant transport and community health impacts. Consequently, there is a need for proactive site selection frameworks that incorporate both subsurface (geotechnical and hydrogeological) and spatial (land use/land cover, distance from roads, built-up areas, and geomorphology) considerations.

The literature is replete with integrated GIS-based multi-criteria decision analysis (MCDA), commonly employing geospatial techniques coupled with Analytical Hierarchy Process (AHP) or fuzzy extensions (Elsadig et al., 2025; Fatoyinbo et al., 2020). This often constitutes an effective means of combining socio-economic, environmental, and physical controls into reproducible site suitability maps (Majidand Mir, 2021; Owoseni, 2023; Ozbay et al., 2021). GIS-AHP approaches allow decision makers to weigh criteria such as proximity to water bodies, depth to groundwater, slope angle, land use/land cover, and access to roads, producing spatially explicit rankings of suitable sites. Validation of such suitability models using independent data or statistical metrics such as Receiver Operating Characteristic (ROC)analysis and area under the curve, AUC, is a common practice that quantifies predictive performance and reliability of the model (Çorbacıoğlu and Aksel, 2023; Richardson et al., 2024).

Despite the strengths of GIS-MCDA, many landfill siting studies place limited emphasis on in-situ geotechnical characterization of liner materials. Natural soils (e.g., lateritic clays or compacted clay liners) remain essential components of landfill base seals in many regions, and their hydraulic conductivity, plasticity, fines content, and compaction behavior directly affect leachate containment capacity. Regulatory guidance and recent reviews indicate typical design targets for low hydraulic conductivity liners (often in the order of 10^{-9}-10^{-7} m/s for compacted clay liners, with geosynthetic options available where native soils are inadequate). Hence, ongoing research continues to refine how local soils can be modified or supplemented to meet containment requirements. Integrating laboratory geotechnical data with GIS criteria, therefore, strengthens the physical basis of suitability assessments and reduces the risk of false positives in mapped suitable areas.

There is an increasing necessity in applied environmental geoscience for case studies that operationalize combined geotechnical-geospatial frameworks in data-scarce, rapidly urbanizing contexts so that planners and policymakers have evidence-based tools for sustainable waste infrastructure siting (Purohit et al., 2026). Prior work in Nigeria and other African countries has demonstrated both the vulnerability of aquifers to landfill leachate and the utility of GIS-AHP mapping, but few studies explicitly couple laboratory geotechnical characterization of potential liner materials with GIS-based AHP weighting (Akinrinmade et al., 2019; Mohammed et al., 2023) and independent ROC validation to produce a defensible decision-support map (Fatoyinbo et al., 2020; Mendes and Lorandi, 2010). This study addresses that gap by applying an integrated geotechnical and geospatial appraisal to identify landfill sites for groundwater and public-health protection in Ado-Odo/Ota and environs, southwestern Nigeria.

The work entails (1) conducting laboratory geotechnical testing in accordance with BS 1377 to evaluate potential mineral seal (liner) materials (moisture content, particle-size distribution, specific gravity, Atterberg limits, dry density and permeability); (2) developing a GIS-based MCDA using six spatial criteria (land use/land cover, distance from lineaments, proximity to roads, depth to water table, soil type, and slope) with weights derived by AHP; and (3) generating and validating a suitability map using weighted overlay and ROC/AUC analysis respectively. This integrated approach that combines subsurface constraints with spatial discrimination and preference criteria yields a scientifically vigorous tool for urban planners targeting groundwater protection and reduction in public-health risks associated with municipal waste disposal.

2. METHODOLOGY

2.1 The Study Area

The study was conducted in Ado-Odo/Ota Local Government Area, Ogun State, southwestern Nigeria, a rapidly urbanizing industrial corridor that has witnessed population growth and escalating municipal solid waste (MSW) generation (Ogwueleka, 2009; Olukanni and Mnenga, 2015). Ota is known for rapid industrialization and urbanization over the past few decades. Ado-Odo/Ota lies within latitude 6°28′00″N to 6°48′00″N and longitude2°50′00″E to 3°18′00″E (Figure 1), and is on average 52 m above mean sea level. It is the second largest of the twenty (20) Local Government Areas in Ogun State (NPC, 2006). The population of the entire state was documented as 3,751,140, with Ado-Odo/Ota contributing to 14% of the total population (261,523 Males and 265,719 Females). The population of Ado-Odo/Ota as of 2006 was 527,242 (NPC, 2006). It was estimated at 644,369 and 900,201 in 2012 and 2022, respectively, at an average growth rate of 3.4% per annum (National Bureau of Statistics, 2018). The climate is tropical, characterized by distinct wet (March/April to October/November) and dry (October/November to March/April) seasons with fairly hot and humid conditions (Omole et al, 2017). The yearly temperature is about 30.62°. Ota typically receives about 147.75mm of precipitation and has 233.94 rainy days annually (Ishaku and Rafee Majid, 2010). The area has tropical rainforest vegetation with trees, thick undergrowth, and shrubs of different types (Agwu et al., 2023).

It falls within the eastern Dahomey (Benin) basin of southwestern Nigeria, which stretches along the continental margin of the Gulf of Guinea (Figure 2), having a sedimentary rock sequence that extends from the eastern part of Ghana through Togo and the Benin Republic to the western margin of the Niger Delta (Onuoha, 1999). According to Omatsola and Adegoke

(1981), the area is underlain by a sedimentary sequence, namely: (i) Recent Alluvium (Quaternary age). (ii) Coastal Plain Sands (Tertiary age – Pliocene). (iii) Ilaro Formation (Tertiary age - Eocene). (iv) Ewekoro Formation (Cretaceous – Paleocene).

The per capita waste generated in Ota and environs has been estimated at 0.58kg/person/day (Olukanni and Akinyinka, 2012). Therefore, using the population figures, the amounts of waste generated in the LGA increased from 305,800 kg/day in 2006 to 373,734 kg/day and 522,117 kg/day in 2012 and 2022, respectively.

Following this trend, the population and amount of waste generated in Ota by the year 2022 would have risen to 900,201 and 522,116kg/day, respectively. These developments have led to increased generation of various kinds of solid wastes such as paper/cardboard, plastic materials, bottles, metal cans, polythene bags, and other combustible miscellaneous waste materials (Olukanni and Mnenga, 2015). Due to a lack of a functional waste management system, improper and indiscriminate solid waste disposal in open dumps (Figure 3) has been commonplace, constituting a potential environmental threat with serious accompanying socio-economic and health implications (Olukanni and Akinyinka, 2012; Olukanni and Mnenga, 2015; Owoseni, 2023; Wuave, 2024).

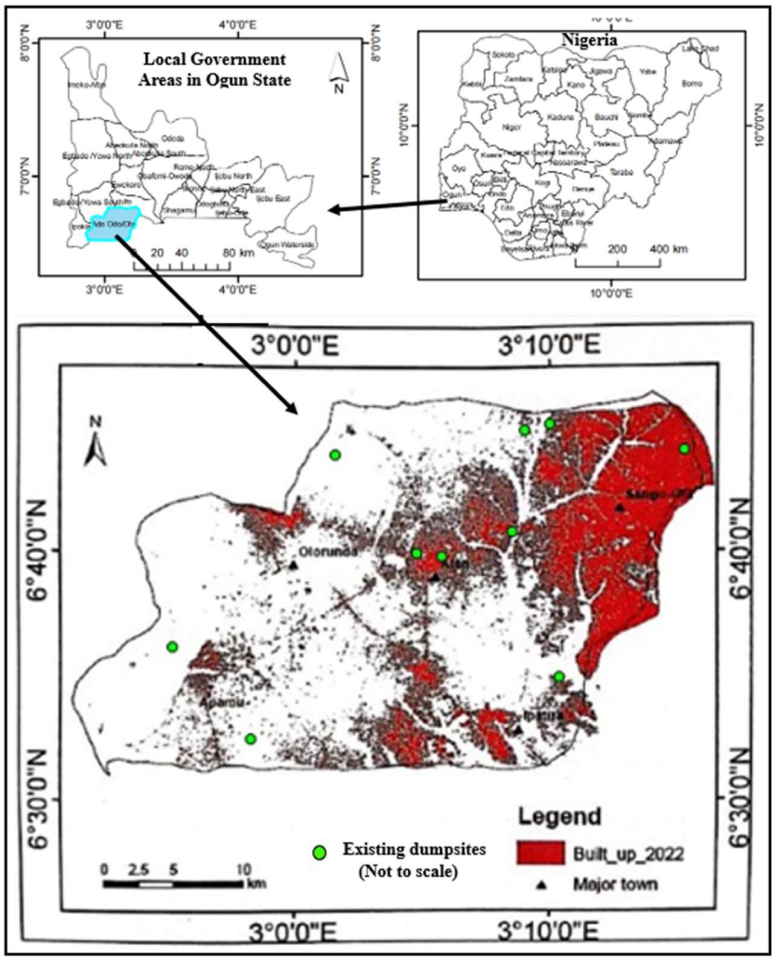


Fig. 1: Location map of the study area showing built-up areas and existing dumpsites.

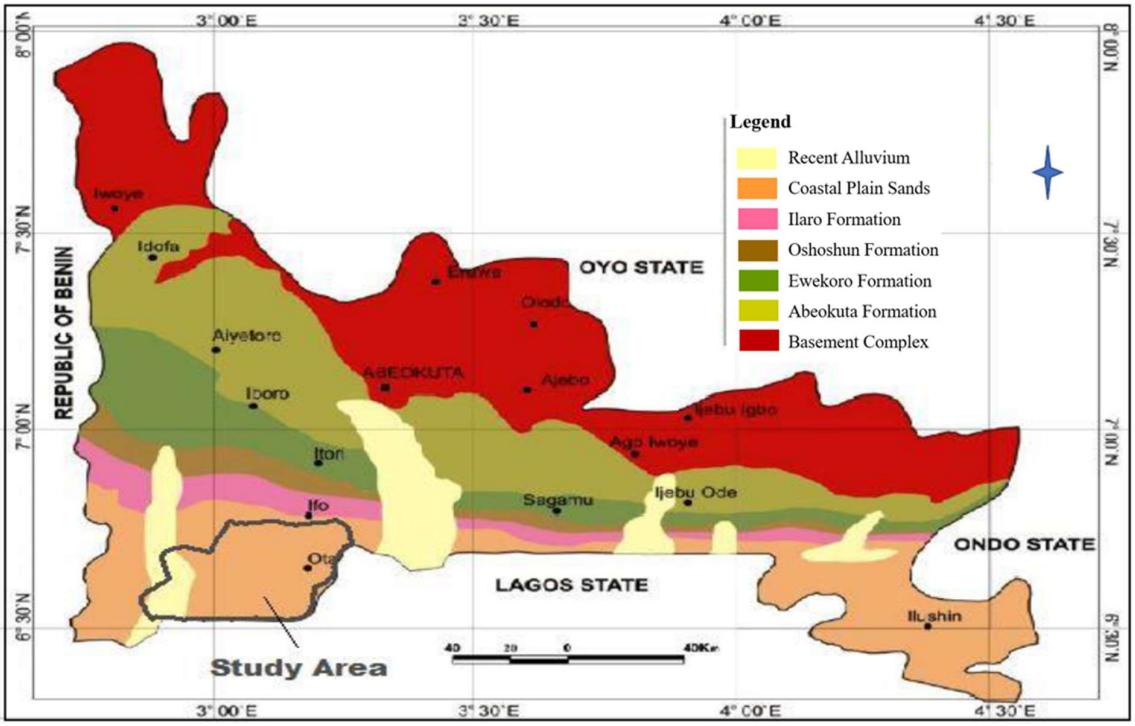


Fig. 2: Geological map of Ogun State showing the study area underlain by Recent Alluvium and Coastal Plain Sands (NGSA, 2006)



Fig. 3: Waste dumpsites (a) Idiroko road, Eye Nkorin (b) Atan-Sango Road (c) Sango-Ifo Road

2.2 Materials and Methods

The appraisal of landfill siting for groundwater and public health protection in the present study followed a 4-step approach, which highlighted integration of AHP, GIS spatial analysis, and geotechnical testing (Figure 4).

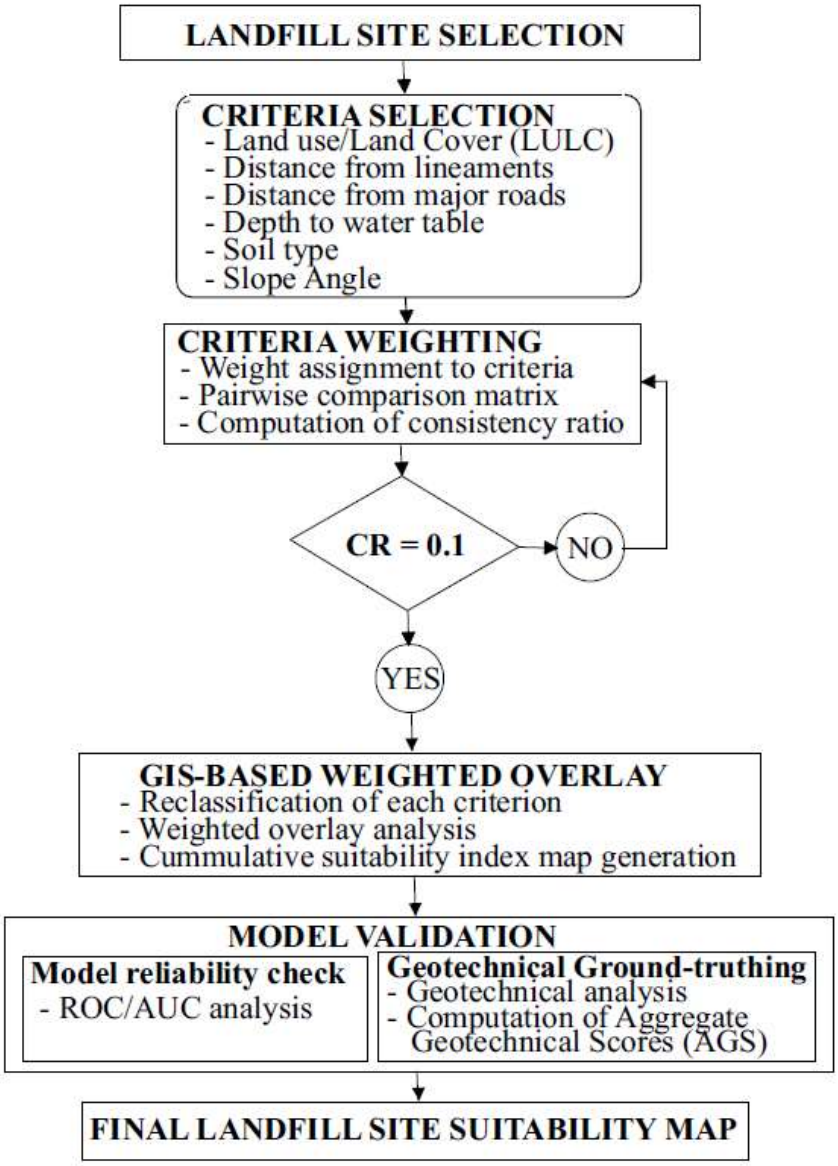


Fig. 4: Flowchart of the methodology for landfill site selection in the study area

2.2.1 Multi-criteria Decision Analysis

Criteria Selection and Data Sources

Landfill siting criteria were defined based on international guidelines, national regulations, and previous studies (USEPA, 2003; FEPA, 1991; Fatoyinbo et al., 2020; Owoseni, 2023; Parameswari et al., 2026). The six major criteria adopted include, (1) Depth to groundwater table - for safeguarding aquifers and reducing risk of leachate infiltration. (2) Land use/land cover (LULC) - to exclude residential, water bodies, industrial, and conservation areas. (3) Soil type - for evaluating natural attenuation and containment properties. (4) Slope- to avoid

erosion, leachate runoff, and instability. (5) Distance from lineament- depicting fracture zones prone to preferential contaminant transport. (6) Distance from major roads - ensuring accessibility while reducing nuisance to residents. LULC was obtained from Landsat imagery, while slope and drainage maps were from Shuttle Radar Topography Mission (SRTM) DEM analysis.

Pre-fieldwork activities involve mapping of existing dumpsites in the study area to ascertain the appropriateness or otherwise of the locations of the existing dumpsites, considering the prevailing rapid urbanization. A total of sixteen (16) representative soil samples were taken systematically across the study area in placed other than the existing dumpsite locations at 1.0m depth each. Laboratory tests, including compaction, permeability, consistency limits, specific gravity, and grain size analysis, were conducted on the samples. These tests were performed in accordance with BS 1377 of the British Standards (1990). Based on recommendations from regulatory organizations such as the British Standards Institution (BSI) and the limitations imposed by earlier researchers, including sample disturbance and limitations in testing methods (Vincent et al., 2020), the laboratory test findings were evaluated and rated. This is with a view to ensuring that the geotechnical parameters obtained are not only accurate in terms of laboratory procedure but are also contextually applicable to practical engineering applications.

Analytical Hierarchy Process (AHP)

Using the Analytical Hierarchy Process (AHP), a multi-criteria decision analysis (MCDA) technique, weights were assigned to adopted site suitability criteria. A pairwise comparison matrix was constructed following Saaty's 1-9 scale (1 for equal importance, and 9 for extreme importance) (Saaty, 1980). Each criterion was compared against others based on its relative significance in landfill suitability. The normalized eigenvector provided the criteria weights. Consistency ratio (CR) was computed to verify the reliability of judgments concerning the consistency of the comparison matrix, with CR $\leq$ 0.1 considered acceptable. The final weights were integrated in ArcMap 10.8 to generate weighted spatial layers for overlay analysis.

2.2.2 Geospatial Analysis

GIS-Based Weighted Overlay

Each criterion was reclassified into suitability ranks using threshold values adapted from guidelines. The weighted overlay analysis was performed in the ArcGIS environment, multiplying each reclassified raster by the respective AHP-derived weight. The cumulative suitability index map was computed following equation (1). The resulting map was categorized into suitability classes.

$$S = \sum_{i=1}^{n} (M_i)\,(N_i) \quad (1)$$

Where M_i = weight of criterion i, and N_i = reclassified suitability score.

2.2.3 Geotechnical Investigation

Sixteen (16) representative soil samples were collected at 1 m depth, with a view to evaluating the subsurface containment potential of the liner soils. Laboratory analyses followed British Standard BS 1377 (1990) procedures. The geotechnical tests conducted include: (i) specific gravity and natural moisture content - to characterize soil state; (ii) particle-size analysis and consistency limits - to classify soils and determine plasticity; (iii) compaction - to determine maximum dry density (MDD) as well as optimum moisture content (OMC); (iv) permeability - to determine hydraulic conductivity, a critical parameter for landfill liners. Design thresholds such as permeability $\leq 1 \times 10^{-7}$ m/s for liners were employed to assess adequacy.

2.2.4 Model Validation

Models were validated using the Receiver Operating Characteristic (ROC) curve and Area Under Curve (AUC) as a way of evaluating the accuracy of model results (Arshad et al., 2020; Richardson et al., 2024). The closer the AUC values are to 1, the higher the predictive accuracy of the model (Çorbacıoğlu and Aksel, 2023; Pourghasemi et al., 2012). The geotechnical test results (permeability, plasticity, and percentage of fines) served as ground-truth data. Predicted suitability classes from the GIS model were compared with geotechnical suitability. The integration of geotechnical laboratory results with GIS-AHP multi-criteria evaluation offered a vigorous, defensible approach to landfill siting. Integration of subsurface soil containment with spatial exclusion factors strengthens groundwater protection and also reduces long-term public health hazards.

3. RESULTS AND DISCUSSION

3.1 Geotechnical Properties of Soils

The results of the geotechnical investigation on residual lateritic soils to serve as potential sanitary landfill liners in the study area are presented in Table 1. The soil samples are largely lateritic clays and silty sands under the USCS. The textural characteristics of soils as granular materials (≤ 35% passing sieve No. 200) or fines (>35% sieve No. 200) in a soil determine, to a large extent, its suitability as a mineral seal (Oeltzschner, 1992; Owoseni and Omotere, 2018). Soil intended for use as a hydraulic barrier in landfill liners requires significant fines content, as a reduction in fines results in decreased hydraulic conductivity. Percentage fines ranged from 25 - 36%, with an average of 31%, indicating a good clay/silt fraction required for containment. The American Association of State Highway and Transportation Officials (AASHTO 1993) classification system, comprising seven groups (A-1 to A-7) with associated subgroups, is valuable for assessing appropriate soil types as landfill liners. The A-1 and A-2 soils are generally preferred due to their low permeability and high load-bearing capacity. The soils are categorized as AASHTO groups A-2-4 to A-2-6 (Figure 5).

3.1.1 Clay activity

Three types of clays have been identified based on their activity values, namely, active clays (activity > 1.25), normal clays (0.75 ≤ activity ≤ 1.25), and inactive clays (activity < 0.75) (Skempton, 1953). The activity of ≤ 1.25 has been specified as a standard value for landfill liners (Oeltzschner, 1992). The clay activity of the investigated soils varied from 0.38 to 1.61, with an average value of 0.89. Six samples (37.5%) possess inactive clays, suggesting dominance of expansive minerals, thereby requiring strict compaction control to prevent swelling. Eight samples (50.0%) have normal clays representing the majority with balanced plasticity and favorable hydraulic performance. The remaining two samples (12.5%) contain active clays, suggesting low-plasticity kaolinitic matrices with potentially higher hydraulic conductivity (Figure 6). Using the benchmark of < 1.25 activity value, fourteen samples (87.5%) are suitable as potential landfill liners.

Table 1: Summary of geotechnical properties of tested soils

Sample code	Natural moisture content	Specific gravity	Particle size distribution				Total Fines (%)	Consistency limits			Clay activity	Compaction characteristics		*k* (m/s)	AGS	Suitability rating
			Gravel (%)	Sand (%)	Silt (%)	Clay (%)		W_L (%)	W_P (%)	*PI* (%)		OMC (%)	MDD kg/m^3			
OT1	5.55	*2.50*	*4.20*	59.90	14.80	21.10	*35.90*	*33.74*	22.15	11.60	*0.55*	16.30	*1875*	1.04E-03	6	Low
OT2	6.40	*2.55*	*3.80*	61.20	16.30	*18.70*	*34.90*	*35.63*	23.40	12.20	*0.66*	16.60	*1805*	7.01 E-04	7	Moderate
OT3	7.10	*2.60*	*4.60*	63.30	19.90	*12.20*	*32.10*	*32.80*	21.05	11.80	*0.96*	16.20	*1758*	5.37 E-04	7	Moderate
OT4	8.40	*2.63*	*2.70*	62.00	15.00	*20.30*	*35.30*	*32.71*	21.50	11.20	*0.55*	17.40	*1820*	3.58 E-04	7	Moderate
OT5	11.30	*2.58*	*3.70*	69.40	16.60	*10.30*	26.90	*38.52*	25.10	13.40	1.31	15.10	1690	5.84 E-04	4	Low
OT6	9.30	2.12	*3.00*	66.90	21.70	*8.40*	*30.10*	*36.65*	23.05	13.60	1.61	14.70	1705	3.12 E-04	4	Low
OT7	6.10	*2.56*	*3.30*	69.20	16.90	*10.60*	27.50	*32.84*	21.15	11.70	*1.11*	16.30	*1833*	4.02 E-04	6	Low
OT8	7.30	*2.53*	*3.50*	67.60	16.70	*12.20*	28.90	*30.91*	20.05	10.90	*0.89*	16.20	*1800*	2.45 E-04	6	Low
OT9	8.15	*2.64*	*3.70*	68.50	16.00	*11.80*	27.80	*30.60*	20.50	10.10	*0.86*	16.40	*1798*	2.46 E-04	6	Low
OT10	7.10	*2.60*	*2.90*	60.90	14.50	21.70	*36.20*	28.96	20.70	8.30	*0.38*	17.10	*1828*	5.92 E-04	5	Low
OT11	9.50	*2.31*	*4.00*	64.60	15.70	*15.70*	*31.40*	*37.47*	19.15	*18.30*	*1.17*	15.20	*1779*	6.15 E-04	8	Moderate
OT12	8.35	*2.69*	*4.20*	68.50	17.50	*9.80*	27.30	*29.99*	19.25	10.70	*1.09*	16.50	*1897*	2.23 E-04	6	Low
OT13	8.70	*2.54*	*3.20*	68.90	13.80	*14.10*	27.90	28.96	18.50	10.50	*0.74*	15.70	*1750*	3.32 E-04	5	Low
OT14	6.65	*2.61*	*5.10*	69.20	13.80	*11.90*	25.70	*29.88*	19.10	10.80	*0.91*	15.50	1700	2.59 E-04	5	Low
OT15	6.20	*2.35*	*5.60*	66.70	15.10	*12.60*	27.70	28.85	18.15	10.70	*0.85*	16.00	*1765*	3.40 E-04	5	Low
OT16	7.75	*2.58*	*4.50*	60.10	15.10	*20.30*	*35.40*	*29.76*	18.30	10.50	*0.56*	16.70	*1800*	3.62 E-04	7	Moderate

W_L = liquid limit, W_P = plastic limit, *PI* = plasticity index, OMC = optimum moisture content, MDD = maximum dry density, *k* = permeability coefficient, AGS = aggregate geotechnical score

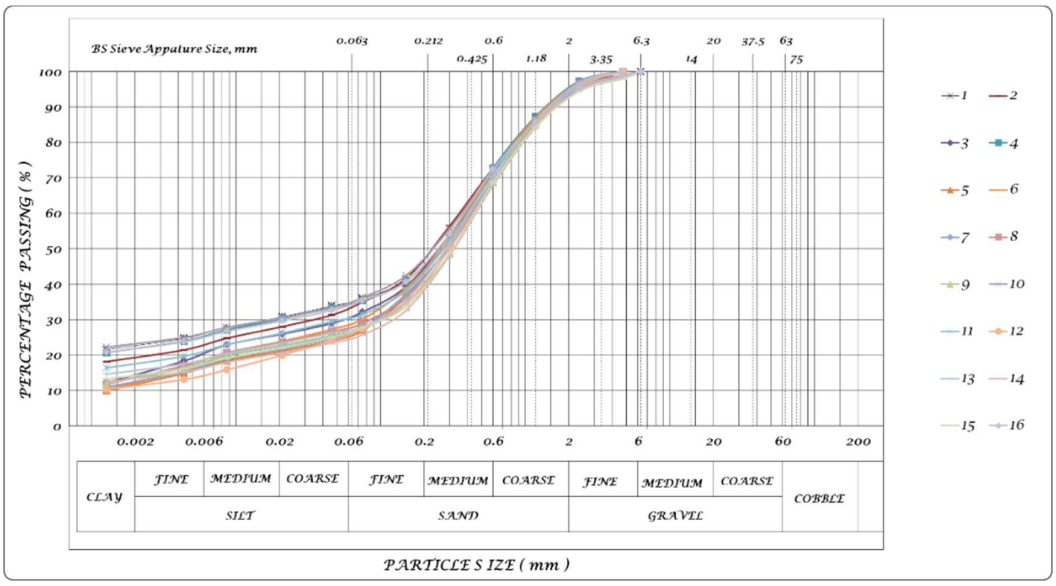


Fig. 5: Particle size distribution curves of representative soil samples showing appreciable clay fractions and amount of fines.

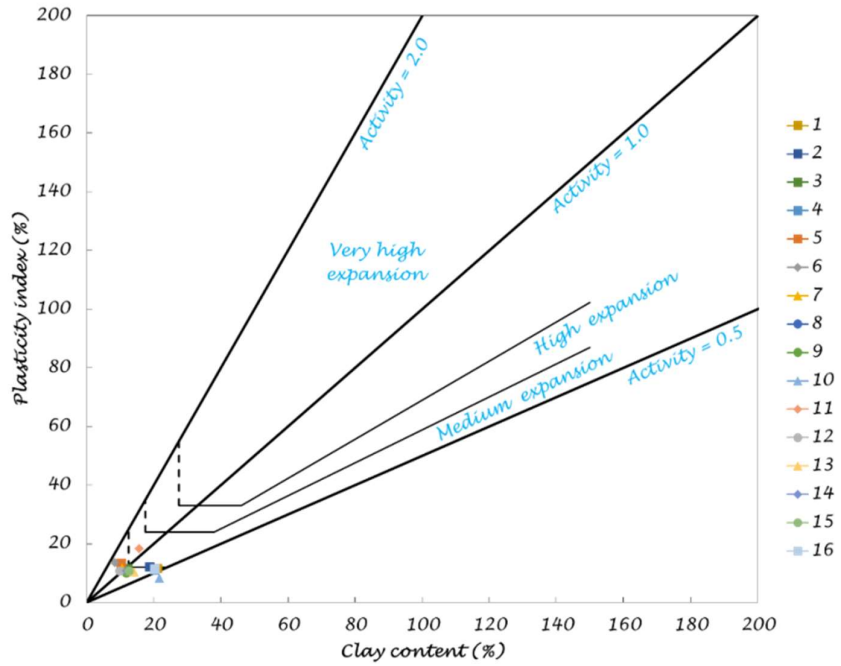


Fig. 6: Skempton's soil activity chart for landfill liner evaluation based on the ratio of plasticity index to clay-size fraction.

3.1.2 Consistency limits

The Atterberg limits constitute another critical geotechnical requirement for the suitability of soils as mineral seals in sanitary landfills. Soils exhibiting high values of liquid limit and plasticity index are considered suitable for mineral sealing purposes in sanitary landfills due to their expected low hydraulic conductivity (Ige and Ogunsanwo, 2009). The recommended consistency limits of soils for use as landfill liners are liquid limit (LL) ≥ 30% and plasticity index (PI) ≥ 15% (Daniel, 1993a; Seymour and Peacock, 1994; Rowe et al., 1995).

The Plasticity index (PI) for tested soils ranged from ~8-18%, placing the soils in the low-medium plasticity category. Out of the sixteen (16) soil samples examined, ten (10) samples, equivalent to 62.5% of the total, meet the LL standard, while only one (1) sample, representing 6.25% of the total samples, fell within this specified PI requirement (Figure 7).

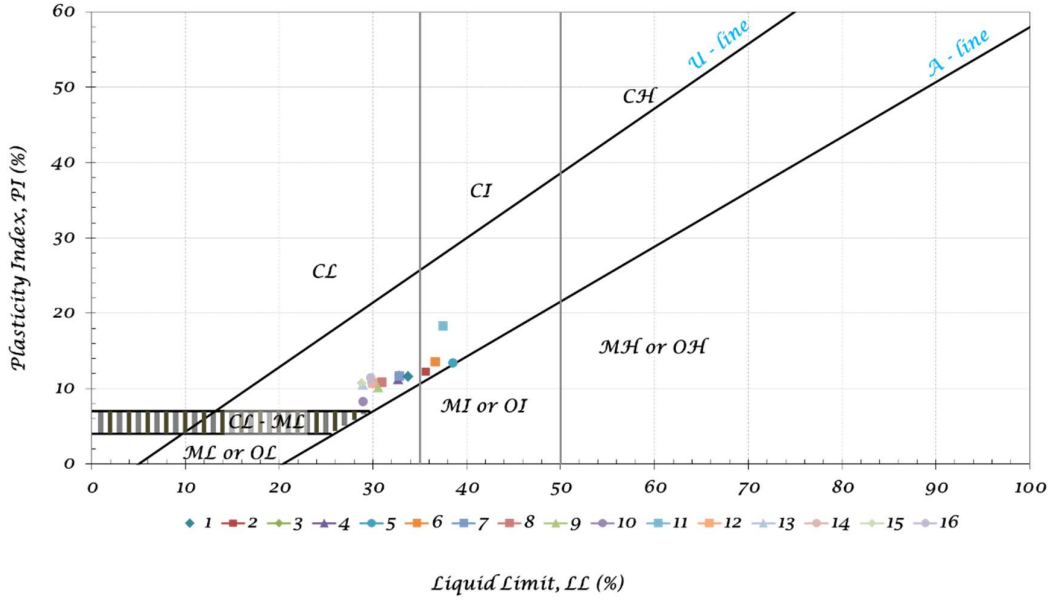


Fig. 7: Atterberg limits chart for the soils

3.1.3 Compaction characteristics

The moisture content-density relationship of soils is another crucial factor for consideration in selecting landfill liners and sites. The hydraulic conductivity of soils is often influenced by the level of compaction. Higher energy of compaction produces lower soil permeability coefficients. The stability and densification of soil grains are determined by the different energy levels to which they are subjected (Owoseni et al., 2012).To be effective, a specified level of compaction must be achieved. Compaction reduces air voids and enhances soil density necessary to function as vital mineral seals in landfill design. The soil can then effectively inhibit the migration of leachate from landfills into surrounding soils and groundwater resources, thereby mitigating environmental degradation.

Maximum dry density (MDD) range from 1690 kg/m³ to 1897 kg/m³ with optimum moisture content (OMC) values from 14.70% to 17.40%. Based on the recommended MDD values of 1710 kg/m³ (ONORMS 2074, 1990) and 1740 kg/m³ (Kabir and Taha, 2006), seven (43.75%) of the sixteen soil samples satisfied the minimum requirements for landfill liners.

3.1.4 Permeability

Permeability is about the most significant factor in landfill design and construction. It determines the rate of migration of fluids from the landfill to the surrounding soil and groundwater. High permeability can lead to objectionable leakage of leachate, and associated risk of soil and groundwater contamination. Low hydraulic conductivity is desirable for landfill liners to prevent or minimize the escape of leachate and gases from landfills into the surrounding environment. Hydraulic conductivity values between 2.23×10^{-4} and 1.04×10^{-3} m/s, slightly higher than standard regulatory limits (10^{-7}– 10^{-9} m/s for engineered liners). The soil samples did not meet the permeability standard of 1 x 10^{-8} m/s to 1 x 10^{-9} m/s specified for liners in sanitary landfills (Daniel and Benson, 1990; Oeltzschner, 1992). However, their usability can be enhanced through an appropriate stabilization method to reduce permeability. Their performance could be improved by compacting them at higher energies and water contents slightly higher than their respective optimum moisture contents (Owoseni and Omotere, 2018).

3.1.5 Aggregate Geotechnical Score (AGS)

Nine (9) geotechnical criteria were assessed in bid to assess the suitability of the soil samples as landfill liners,, namely, specific gravity, % gravel fractions, % clay fractions, % fines, liquid limit (W_L), plasticity index (PI), clay activity (A_c), maximum dry density (MDD), and permeability coefficient (k). Each criterion is significant in determining suitability of soils as liners, and landfill sites. Each geotechnical parameter was assigned one (1) point, and the Aggregate Geotechnical Score (AGS) is computed as the overall points scored by a soil sample for meeting any of the standard specifications. Whatever any soil sample scores out of nine determines its suitability level (Fatoyinbo et al, 2020). Table 2 indicates three (3) suitability categories, namely, non-suitable, "moderately suitable, and highly suitable for Total Geotechnical Point (TGP) ranges of 1-3, 4-6, and 7-9, respectively. Based on the geotechnical rating of each soil, geotechnical suitability scores were given.

Table 2: Total geotechnical point ranges and assigned suitability (Fatoyinbo et al., 2020)

Total geotechnical point ranges	Geotechnical suitability scores	Assigned suitability
1-3	2	Unsuitable
4-6	5	Average suitability
7-9	9	Suitable

This suggests that while soils provide natural attenuation, additional compaction or lining amendments may be required for compliance. Soils exhibit moderate suitability as landfill liners but may require engineering improvements such as addition of bentonite or densification to achieve low permeability targets.

3.2 Criteria Weighting and AHP Outcomes

The pair-wise comparison matrix for site suitability criteria is shown in Table 3. The comparison matrix is adjudged reasonably consistent with the Consistency Ratio of 0.07 obtained, a value within the acceptable range (CR $\leq$ 0.1). Relative weights indicate that Depth to groundwater has the highest, followed by LULC, soil type, slope, lineament, and road proximity. GIS-based thematic layers of the criteria are presented in Figure 8. Groundwater was assigned the highest weight to reflect its critical role in public health protection. This is consistent with global best practices and ensures that groundwater vulnerability is prioritized in site suitability analysis (Collin and Melloul, 2003; Lavoie et al., 2015).

Table 3: Pair-wise comparison matrix for the evaluation criteria

Evaluation Criteria	DG	LULC	ST	DL	DR	SA	Weight	% Weight
Depth to groundwater, DG (m)	1.00						0.502	50.2
Land use/land cover, LULC	0.20	1.00					0.242	24.2
Soil type, ST	0.20	0.25	1.00				0.094	9.4
Distance from lineament, DL (m)	0.11	0.14	0.50	1.00			0.038	3.8
Distance from roads, DR (km)	0.14	0.17	0.20	0.21	1.00		0.037	3.7
Slope angle, SA (°)	0.20	0.25	0.21	0.30	0.30	1.00	0.088	8.8

Consistency ratio (CR)= 0.07

3.3 GIS–Based Suitability Mapping

The results of weighted overlay analysis indicate (i) very suitable areas (about 12.17 km² or1.41%); (ii) suitable areas (775.56 km² or 89.96%);(iii) unsuitable areas (74.34 km² or 8.62%) as shown in Table 4. Some of the existing dumpsites have been overtaken by rapid urbanization necessitating new sites suitable for today's urban setting.

Identified suitable zones largely fall in areas of low settlement density (Figure 9), low slopes (< 8%), deep water tables (> 140 m), and clayey soils. Unsuitable zones clustered around settlements, roads, lineament zones, and shallow groundwater areas.

Four potential sites have been identified in the study area for sustainable landfill which can guide urban planners and policy makers towards safeguarding urban groundwater, reducing public health risks, and informing rational waste management planning in the urbanizing and industrializing corridor (Figure 10).

Table 4: Landfill site suitability classification in the study area

Suitability class	Area (km²)	Area (%)
Very suitable	12.17	1.41
Suitable	775.56	89.96
Unsuitable	74.34	8.62

3.4 Model Validation (ROC/AUC Analysis)

ROC curve analysis using geotechnical suitability as validation dataset produced an AUC = 0.816, indicating 81.6% prediction accuracy (Figure 11). This indicates good agreement between predicted GIS suitability classes and laboratory-based soil containment potential. The integrated geotechnical and geospatial framework is robust and reliable for guiding landfill siting decisions in the study area.

3.5 Implications for Groundwater and Public Health Protection

Integrating soil geotechnical data reduces overestimation of suitable sites, ensuring groundwater safety. GIS-AHP provides planners with a replicable decision-support tool for identifying landfill sites that balance accessibility, environmental sustainability, and public health. Findings highlight the importance of multi-disciplinary approaches, combining spatial, hydrogeological, and engineering datasets, for sustainable waste management in developing regions.

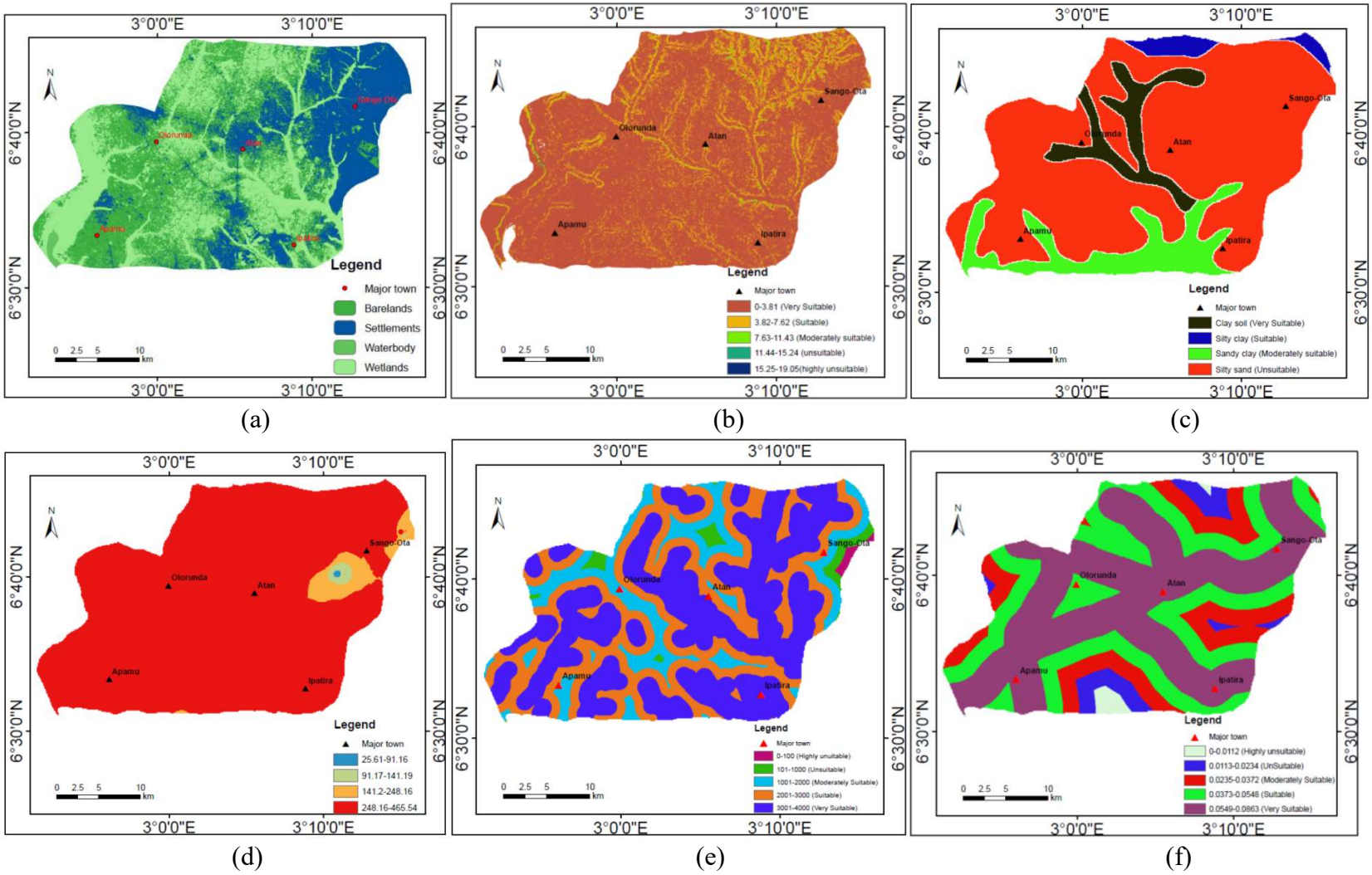


Fig. 8: GIS-based thematic layers: (a) land use/land cover, (b) slope angle, (c) soil type, (d) depth to groundwater, (e) distance from lineaments, (f) distance from roads.

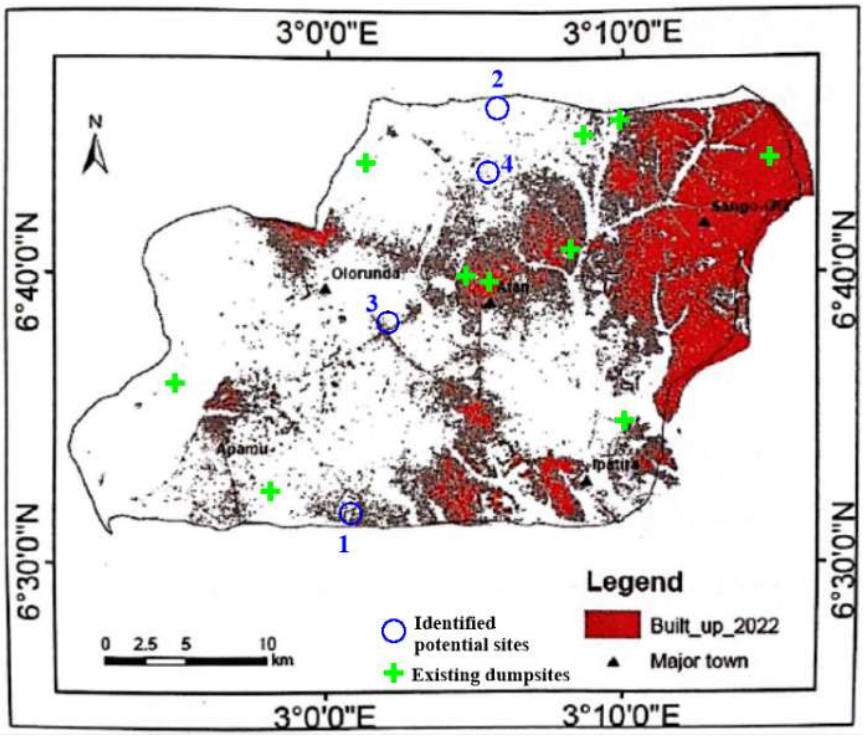


Fig. 9: Existing dumpsites, built-up areas and identified potential sites

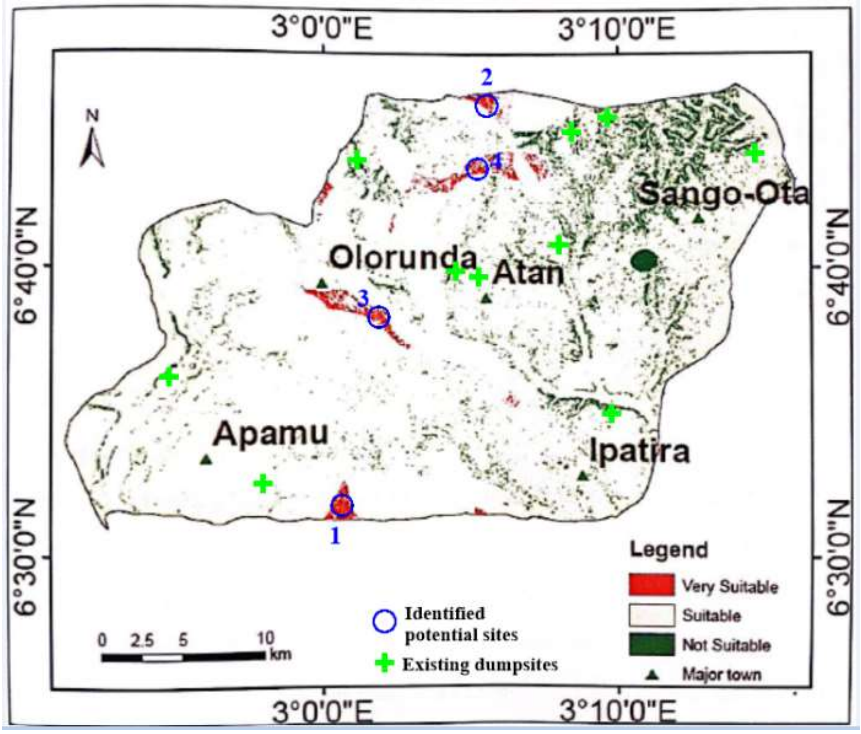


Fig. 10: Landfill suitability map from GIS-AHP weighted overlay analysis

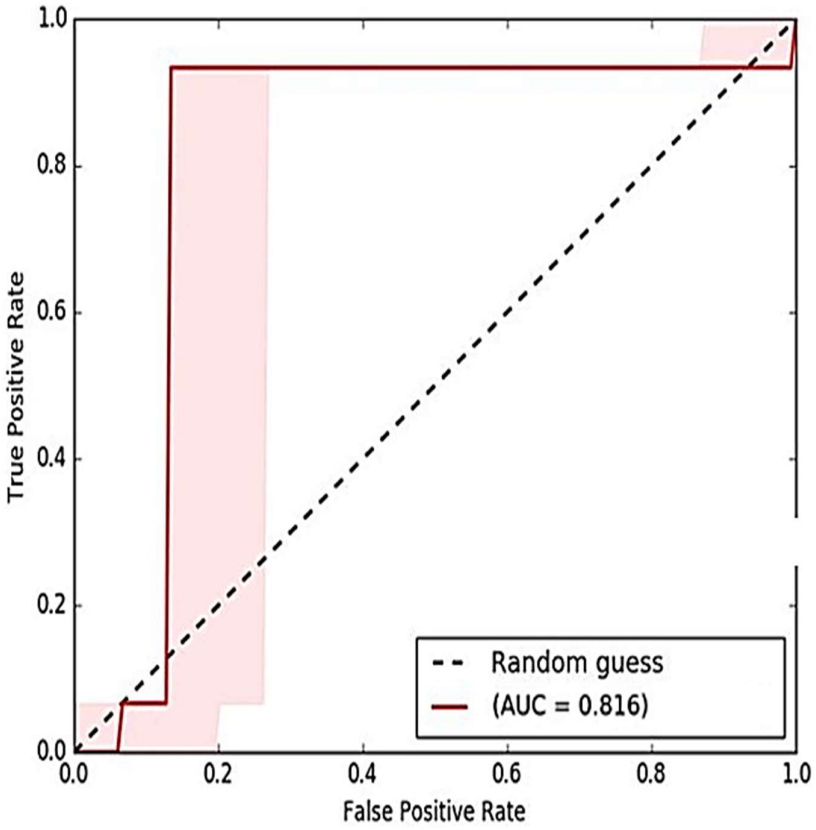


Fig. 11: ROC curve validating landfill suitability map

4. DISCUSSION

4.1 Geotechnical Suitability of Soils

The geotechnical results indicate that soils in the study area are lateritic with moderate fines content (25.7% - 36.2%) and plasticity indices (8.3%–18.3%), values broadly consistent with recommended ranges for landfill liners (Daniel, 1993b; Rowe et al., 1995). These properties suggest that natural soils can provide partial containment capacity; however, measured hydraulic conductivities (7.01×10^{-4}–1.04×10^{-3} m/s) exceed the regulatory threshold of $k \leq 5 \times 10^{-10}$ m/s for compacted clay liners (Daniel, 1993b; Oeltzschner, 1992; Seymour and Peacock, 1994). Similar findings were reported in Nigeria and other tropical regions, where natural soils required compaction, bentonite amendment, or use of geosynthetic clay liners to meet design standards (Fatoyinbo et al., 2020; Owoseni and Omotere, 2018). This highlights the importance of integrating geotechnical evaluation into site selection frameworks to avoid over-reliance on GIS.

4.2 Geospatial Analysis and Criteria Weighting

The AHP analysis prioritized depth to groundwater (50.2%) and land use/land cover (24.2%) as the most critical factors.This is consistent with studies in arid and semi-arid regions that emphasized groundwater vulnerability as the primary constraint in landfill siting (Seraiche et al., 2025). Road proximity, while often important for operational access, was given the lowest weight (3.7%), reflecting the overriding need to protect aquifers in densely populated and industrialized areas. The GIS-AHP integration produced a suitability map in which 1.41% of the study area was classified as very suitable, similar to proportions reported in

Ethiopia (1.9%) (Balta and Gamo, 2024) and Iran (2.3%) (Pasalari et al., 2019), suggesting that truly optimal landfill sites are often scarce in urbanizing environments.

4.3 Model Validation and Reliability

The ROC validation yielded an AUC of 0.816, demonstrating good predictive performance. This is within the range of accuracy (0.78-0.87) reported in other GIS-MCDA landfill studies (Elkhrachy et al., 2023). Validation is often neglected in landfill siting research, leading to uncertainty in policy uptake. By cross-checking GIS predictions with laboratory geotechnical data, this study demonstrates the value of a hybrid framework that increases model credibility and applicability for planners and environmental regulators.

4.4 Implications for Groundwater and Public Health

Groundwater is the primary source of drinking water for many communities in southwestern Nigeria (Egbinola and Amanambu, 2014; Idowu and Ojo, 2024; Owoseni, 2024). Without proper siting and engineered containment, landfill leachate can introduce heavy metals, nitrates, and pathogens into aquifers, leading to gastrointestinal illness, chronic toxicity, and long-term ecological degradation (Akhtar et al., 2021; Parvin and Tareq, 2021). By integrating geotechnical testing and geospatial analysis, this study advances a robust approach that not only identifies suitable sites but also evaluates their capacity to safeguard groundwater. This framework directly supports the United Nations Sustainable Development Goal 6 (clean water and sanitation) and Goal 3 (good health and well-being).

5. CONCLUSION

This study demonstrates the value of integrating geotechnical characterization with geospatial multi-criteria decision analysis for landfill site selection in Ado-Odo/Ota Local Government Area, Ogun State, Nigeria. The geotechnical tests revealed that some of the soils (about 31%) possess fairly favorable properties in some locations - moderate permeability, appreciable fines content, and fairly suitable compaction behavior - making those ones adaptable natural liner materials for landfill containment. The GIS-based suitability analysis, weighted through the Analytical Hierarchy Process, identified limited areas (1.41%) as highly suitable, with most parts(89.96%) of the land moderately suitable for landfill development. Validation using ROC analysis (AUC = 0.816) confirmed the robustness of the adopted framework. The findings highlight that sustainable landfill planning requires not only spatial exclusion criteria but also rigorous assessment of soil behavior to minimize leachate migration and protect groundwater. They have important implications for policy and practice. By integrating spatial decision support with field-based geotechnical assessment, this study advances a comprehensive framework that can guide regulators, municipal planners, and environmental managers in selecting landfill sites that minimize groundwater contamination risks and protect public health, and promote resilient urban development in the face of growing waste management challenges. In practical terms, the approach provides a pathway to reduce the environmental and health risks posed by indiscriminate waste disposal in Nigeria and similar developing regions.

Future work should incorporate hydrogeological modeling of contaminant migration, long-term groundwater monitoring, and socio-economic assessments of landfill siting decisions. Ultimately, the adoption of evidence-based landfill siting frameworks will contribute to safer waste management, groundwater sustainability, and the achievement of global targets such as Sustainable Development Goals (especially SDG 3 and SDG6).

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