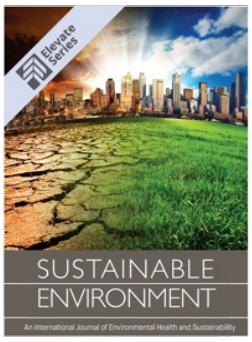

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POLLUTION, WASTE AND WATER MANAGEMENT | RESEARCH ARTICLE

GIS-Integrated Analytical Hierarchy Process (AHP) for optimal landfill site selection in Kadoma City, Zimbabwe

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ABSTRACT

Effective waste management remains a pressing challenge in rapidly urbanizing cities like Kadoma, Zimbabwe, where limited land availability complicates landfill siting. Despite the global prevalence of landfilling, poor site selection in such contexts can trigger groundwater contamination, odour issues, and public health risks. This study addresses the absence of structured landfill siting research in data-scarce African cities by applying a GIS-integrated Analytical Hierarchy Process (AHP) and Multi-Criteria Evaluation (MCE). AHP was employed to assign relative weights to twelve spatial variables—including slope, elevation, proximity to rivers, roads, and built-up areas—through structured pairwise comparisons. MCE integrated these weighted factors within a GIS platform to generate a final suitability map. Results indicate that only 5.2 % of Kadoma's area is suitable for landfill development, while the majority is constrained by dense urbanization. The suitability map, converted into a shapefile for visualization and area calculation, offers a practical tool for urban planners, environmental agencies, and local authorities to inform sustainable waste infrastructure development. This study demonstrates the applicability of GIS-AHP approaches in rapidly growing, resource-limited urban environments and underscores the need for localized, data-driven decision-making in landfill site selection.

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KEYWORDS
Multi-criteria evaluation; analytical hierarchy process; AHP; landfill; suitability map

1. Introduction

Sustainable solid waste management remains a pressing challenge across African countries, with numerous reports highlighting the escalation of water contamination, respiratory illnesses, and other health risks linked to poor waste disposal practices (Asori et al., 2022; Marshall & Farahbakhsh, 2013; Zhang et al., 2024). Zimbabwe is no exception; rapid urbanization, particularly in cities like Kadoma, has exacerbated municipal solid waste management issues (Chikobvu & Makarati, 2011; Dahwa et al., 2023; Zhongove et al., 2024). Due to infrequent waste collection services, many communities resort to burning waste, releasing hazardous pollutants such as dioxins into the atmosphere (R. V. Mangizvo, 2010; Musendekwa, 2024), while others practice indiscriminate dumping in open spaces. Kadoma's growing population, recorded at 117,380 in 2022, coupled with urban sprawl, has intensified solid waste volumes and strained existing municipal services. As a result, land availability for proper landfill siting has diminished, with significant conflicts arising from competing land uses, particularly mining and agriculture. The Environmental Management Act (Chapter 20:27) and the EMA (Environmental Management Agency) guidelines emphasize the need for sustainable waste management and zoning compliance, yet cities continue to face infrastructural and regulatory constraints.

Recent studies across the African continent has increasingly turned to geospatial technologies and decision-support frameworks to address the multifaceted problem of optimal landfill site selection, reflecting a broader shift toward sustainable and data-driven urban planning (Desta et al., 2025; Moumane et al., 2025; Oyinloye et al., 2023). These approaches have demonstrated the viability of integrating Geographic Information Systems (GIS), remote sensing, and Multi-Criteria Decision Analysis (MCDA) methods—especially the Analytical Hierarchy Process (AHP)—in tackling solid

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waste management challenges that are both context-specific and regionally resonant. For example, Moumane et al. (2025) conducted a seminal study in Kenitra Province, Morocco, where they employed a GIS-AHP framework to systematically assess spatial constraints and opportunities for landfill siting. Their work emphasized the alignment of technical site suitability with national sustainable development objectives, illustrating how structured geospatial models can mitigate environmental and social conflicts often associated with landfill siting (Moumane et al., 2025). Importantly, their methodology combined satellite-derived datasets, land-use classifications, and expert-weighted decision criteria, yielding spatially explicit outputs that were not only scientifically robust but also policy-relevant (Moumane et al., 2025). Similarly, in Nigeria, Oyinloye et al (2023)) utilized GIS-based MCDA techniques to evaluate landfill siting in rapidly growing peri-urban zones, integrating slope, soil type, land use, and hydrological proximity. Their findings revealed that spatial tools can effectively reconcile land availability constraints with public health imperatives, particularly in areas experiencing high population growth and inconsistent municipal oversight (Oyinloye et al., 2023). In Ethiopia, Desta et al. (2025) demonstrated how the incorporation of AHP within a GIS environment provided local planners with a dynamic platform to balance ecological integrity with infrastructural demands, especially in regions with significant agricultural and conservation land uses. These emerging African case studies not only affirm the versatility of geospatial MCDA approaches but also highlight a growing continental consensus on their applicability and adaptability. What distinguishes these studies is their attention to contextual heterogeneity—recognizing that ecological, socio-political, and infrastructural conditions vary widely across African urban landscapes, thus requiring tailored geospatial models. For Zimbabwe, where spatial planning often contends with historical land tenure complexities and ongoing resource competition (Matsa et al., 2020), such approaches offer a methodological bridge between empirical rigour and practical governance (Matsa et al., 2020). By embedding the GIS-AHP framework within broader regional trends in geospatial waste management research, this study responds directly to the methodological gap in Zimbabwean literature and advances the scholarly conversation on spatial equity and environmental sustainability in Southern Africa. Moreover, incorporating insights from comparable African contexts provides a comparative lens through which the uniqueness of Kadoma's urban morphology, socio-environmental dynamics, and governance structures can be more effectively interrogated. The present study, therefore, situates itself at the intersection of geospatial innovation and applied urban sustainability, contributing not only to the body of local urban environmental planning but also to the broader epistemology of African spatial decision-making.

Effective landfill siting is a complex spatial decision-making problem requiring the integration of multiple overlapping criteria—environmental protection, social acceptability, and infrastructural efficiency—within a geographic framework (Al Awadh & Mallick, 2024; Alavi et al., 2013; Shukor et al., 2024). Traditional approaches are often hampered by data fragmentation, limited technical capacity, and inadequate stakeholder engagement (Rahmat et al., 2017; Randazzo et al., 2018; Şener et al., 2010). In this context, GIS-integrated Multi-Criteria Decision Analysis (MCDA) tools, particularly the Analytical Hierarchy Process (AHP), offer significant advantages (Rahmat et al., 2017; Wang et al., 2009). GIS enables the spatial handling of large, diverse datasets, while AHP facilitates the structured prioritization and weighting of criteria, enhancing the transparency, objectivity, and efficiency of landfill site selection (Desta et al., 2023; Singh et al., 2023). For Kadoma City, the integration of GIS and AHP provides a pragmatic solution to local planning challenges. It allows municipal authorities to systematically evaluate factors such as proximity to water bodies, settlement patterns, infrastructural accessibility, and exclusion zones like mining areas and agricultural land. Moreover, GIS-based AHP supports participatory planning by incorporating stakeholder inputs into the decision-making process (Al Awadh & Mallick, 2024; Bechroune et al., 2024), aligning technical outcomes with community values and enhancing the likelihood of public acceptance (Manyoma-Velásquez et al., 2020).

Recognizing the importance of public engagement, this study underscores the need for landfill siting processes to involve local stakeholders actively. Through AHP, community preferences can be quantified and integrated, ensuring that selected sites not only meet technical and environmental standards but also gain broader societal support (Mondal et al., 2024). We hypothesize that the integration of GIS and AHP significantly improves the accuracy, transparency, and sustainability of landfill site selection, ultimately contributing to more resilient urban waste management systems.

2. Materials and methods

2.1. Study area

Kadoma City is located at 29°55′30″E, 18°19′30″S, within Sanyati District of Mashonaland West Province, Zimbabwe (Figure 1). It lies 141 kilometres southwest of Harare along the Harare-Bulawayo highway and is situated at an elevation of 1,183 meters above sea level. Kadoma attained city status on 17 March 2000, making it one of Zimbabwe's newest urban centres. According to the 2022 national census (ZIMSTAT, 2022), the city's population stands at 117,380, reflecting a 3% increase from 2002. This steady population growth, driven largely by rural-urban migration (Maponga et al., 2013), has led to increased volumes of solid waste, urban sprawl, and mounting pressure on municipal waste management services, thereby intensifying the need for strategic landfill site selection.

Economically, Kadoma's development is anchored in extensive mining and agricultural activities (Remigios & Never, 2010). The city lies in the heart of Zimbabwe's mining belt, hosting major operations

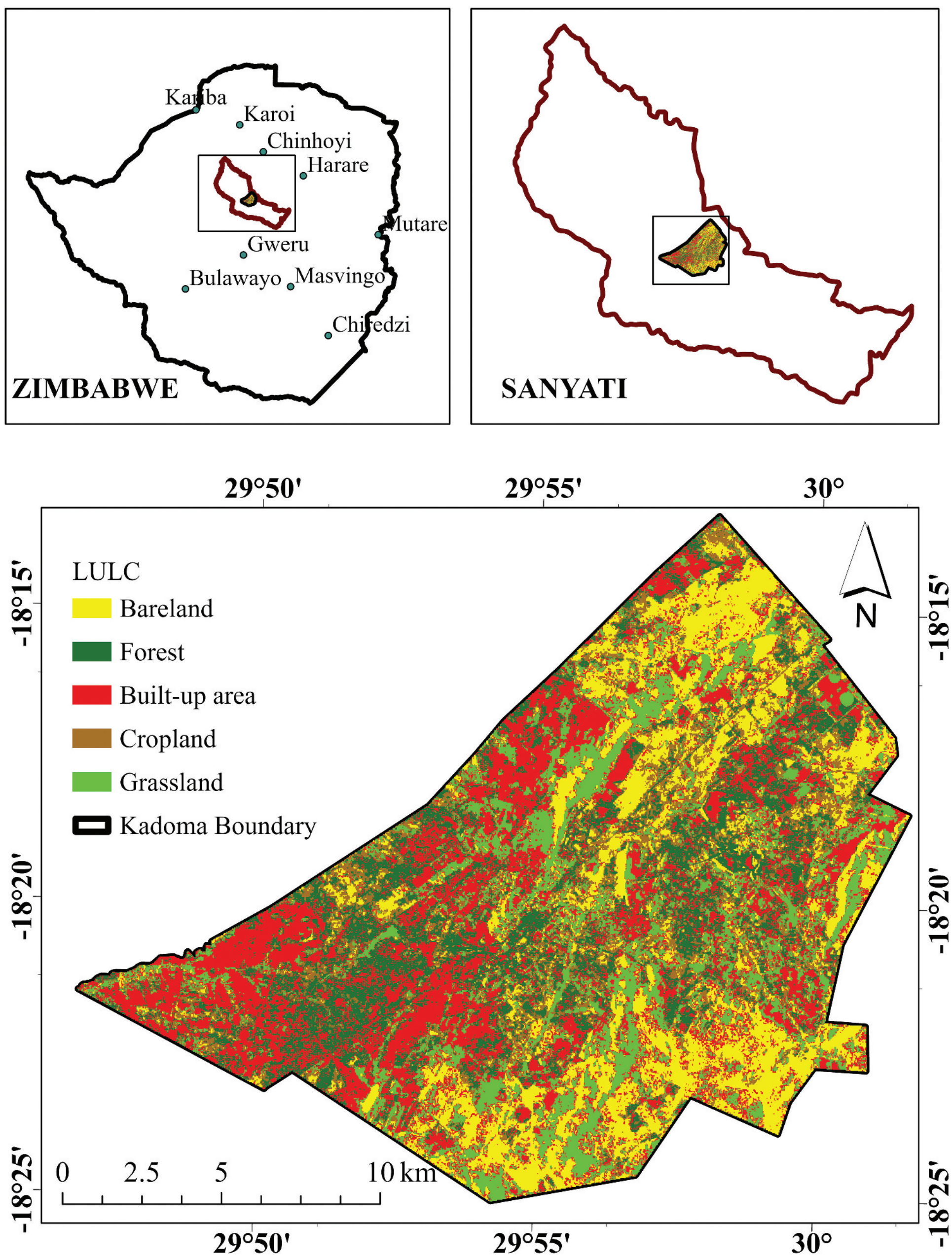

Figure 1. Location of Kadoma City in Sanyati district, Zimbabwe.

such as the Cam and Motor gold mines, alongside significant nickel and copper mining activities. The presence of active mining zones restricts land availability for landfill development, as areas near extractive industries are generally unsuitable for waste disposal due to potential land use conflicts, groundwater contamination risks, and regulatory exclusions. Similarly, agricultural areas—particularly those supporting commercial crop and livestock production—limit viable options for landfill siting to prevent disruption of food security and livelihoods (Sheunesu, 2007). Kadoma's physical landscape features a mix of flat to gently undulating terrain, interspersed with river systems such as the Mupfure River. These rivers, along with wetlands and flood-prone zones, serve as critical environmental buffers that must be excluded from landfill development to protect ecological health and minimize contamination risks. Moreover, patches of dense vegetation and protected natural areas further constrain spatial planning decisions by acting as exclusion zones during site selection. Thus, Kadoma City presents a complex spatial matrix where urban expansion (R. Mangizvo, 2009), economic activities, and environmental sensitivities must be carefully balanced in landfill planning. Understanding these dynamics is essential to ensure that new waste disposal facilities are both environmentally sustainable and socially acceptable within the broader urban development framework.

2.2. Methodology flowchart

The methodology flowchart (Figure 2) for landfill suitability analysis in Kadoma City illustrates a systematic workflow that integrates geospatial data, thematic mapping, and multi-criteria decision-making techniques to identify the most suitable sites for landfill development. The process begins with the aim of the study, which is to determine suitable landfill locations, guided by identification criteria such as soil type, geology, land use, elevation, slope, NDVI, wind speed, and distances from built-up areas, roads, rivers, railways, and powerlines. Next, data acquisition involves collecting both primary data (from global datasets such as the Harmonized World Soil Database, WorldClim, Shuttle Radar Topography Mission, and OpenStreetMap) and secondary data (from SOI toposheets and geological maps of Zimbabwe). These datasets are processed and digitized into thematic maps representing the identified spatial criteria. In the data analysis stage, thematic map layers are resampled and reclassified into standardized classes. These layers are then integrated through the Analytic Hierarchy Process (AHP), which involves constructing a pairwise comparison matrix, computing criteria weights, and checking the consistency ratio to ensure reliability. Finally, the weighted and reclassified layers are overlaid to generate a final suitability map, which highlights optimal zones for landfill placement by balancing environmental, geological, and socio-economic considerations.

2.3. Geospatial datasets

In this study, twelve spatial variables (Table 1 and 2, Figures 2 and 3)—slope, wind, road, built-up area, elevation, geology, soil, river, railway lines, powerlines, land use/land cover (LULC), and the Normalized Difference Vegetation Index (NDVI)—were utilized to develop a landfill suitability map for Kadoma City, Zimbabwe, using the Analytical Hierarchy Process (AHP). All spatial data processing, analysis, and map generation were conducted using ArcGIS Pro 3.0.

The preparation of each geospatial dataset involved multiple steps including data acquisition, preprocessing, and standardization to ensure compatibility for multi-criteria analysis. Elevation data were derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a spatial resolution of 30 meters (Table 2), downloaded from the United States Geological Survey (USGS) Earth Explorer. The DEM was used to generate the slope layer through the 'Slope' tool in ArcGIS Pro. The resulting slope map was reclassified into suitability classes based on thresholds favoring gentler slopes for landfill development. Wind data were sourced from the WorldClim version 2.1 dataset, providing monthly mean wind speed values at a spatial resolution of 1 km. Using ArcGIS Pro's 'Resample' tool, the wind layer was resampled to match the 30-meter resolution of other layers. Suitability classes were defined by reclassifying wind speeds, as higher winds can influence the spread of odors and airborne waste particles. The road network data, including primary and secondary roads, were extracted from Open Street Map (OSM) using the Quick OSM plugin and imported into ArcGIS Pro. A Euclidean Distance analysis was performed to create a continuous surface showing proximity to roads. Areas closer to major roads were

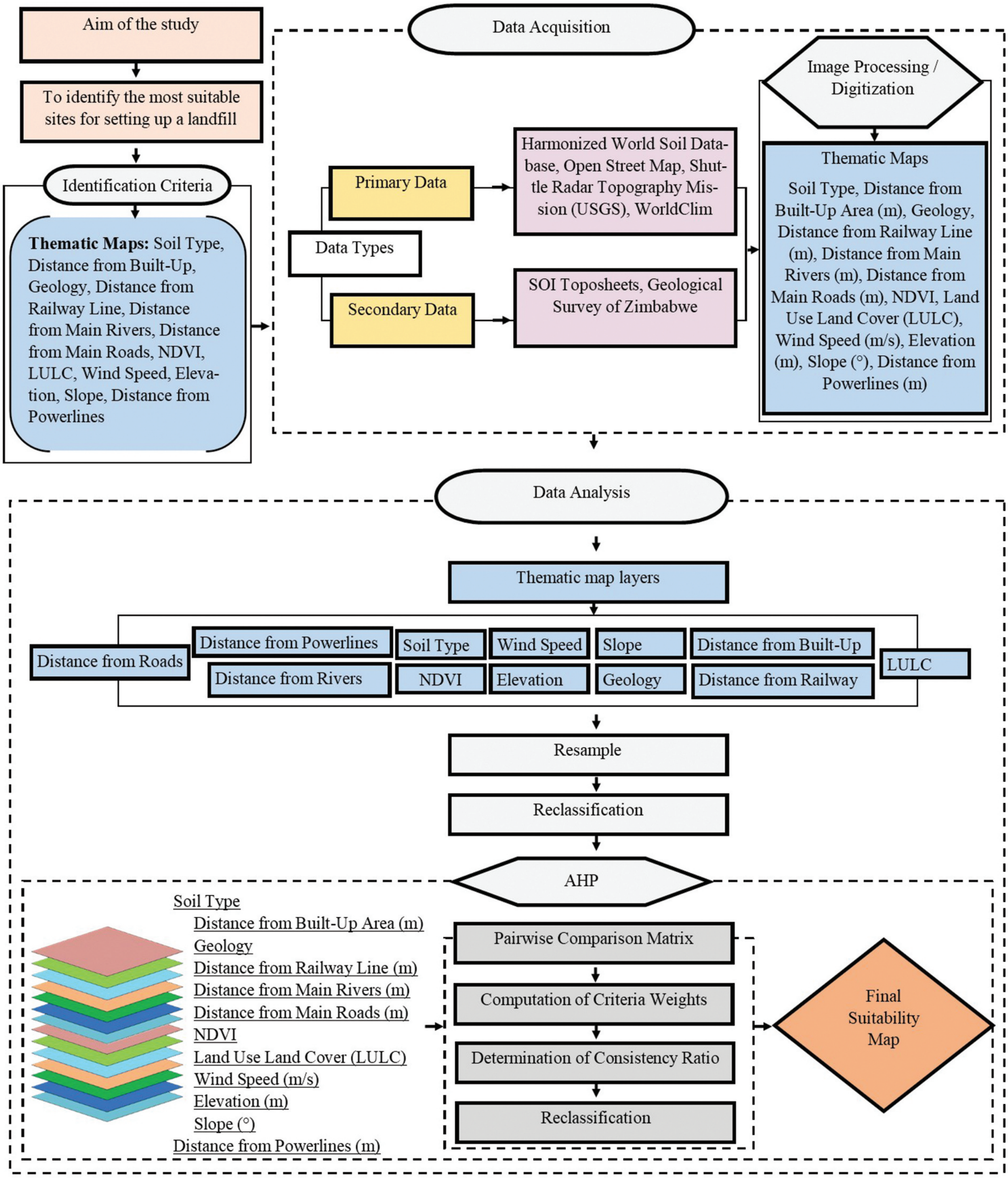

Figure 2. Methodology flowchart for developing a landfill site suitability model in Kadoma City, Zimbabwe, integrating spatial datasets, thematic map generation, multi-criteria analysis, and analytic Hierarchy process (AHP) to produce a final suitability map.

considered more suitable for ease of access, while proximity thresholds were reclassified based on standard landfill siting guidelines. Built-up area data were extracted from the LULC classification generated from Sentinel-2 imagery (10-meter resolution) downloaded from Copernicus Open Access Hub. The supervised classification technique was applied using the Maximum Likelihood Classifier in ArcGIS Pro, after preprocessing steps including atmospheric correction and cloud masking (Aksoy & San, 2019; Zelenović Vasiljević et al., 2012). The built-up layer was then buffered using a 500-meter exclusion zone to avoid landfill placement near residential areas. The elevation layer was directly derived from the same SRTM

Table 1. Pairwise comparison matrix

	Item number	1	2	3	4	5	6	7	8	9	10	11	12
Item number	Factor	Slope	Wind	Road	Built-up area	Elevation	Geology	Soil	River	Railway line	Powerlines	LULC	NDVI
Pairwise comparison matrix													
1	Slope	1.00	4.00	0.33	0.25	1.00	0.33	0.50	1.00	3.00	2.00	0.50	0.50
2	Wind	0.25	1.00	0.33	0.13	0.20	0.14	0.17	0.17	0.33	0.50	0.20	0.20
3	Road	3.00	3.00	1.00	0.20	0.50	0.33	0.33	0.33	1.00	2.00	0.50	0.50
4	Built-up area	4.00	8.00	5.00	1.00	3.00	2.00	2.00	1.00	5.00	5.00	1.00	3.00
5	Elevation	1.00	5.00	2.00	0.33	1.00	1.00	0.50	0.50	3.00	3.00	2.00	3.00
6	Geology	3.00	7.00	3.00	0.50	1.00	1.00	1.00	0.50	2.00	4.00	0.50	2.00
7	Soil	2.00	6.00	3.00	0.50	2.00	1.00	1.00	2.00	4.00	4.00	2.00	2.00
8	River	1.00	6.00	3.00	1.00	2.00	2.00	0.50	1.00	4.00	5.00	0.50	2.00
9	Railway line	0.33	3.00	1.00	0.20	0.33	0.50	0.25	0.25	1.00	1.00	0.33	0.50
10	Powerlines	0.50	2.00	0.50	0.20	0.33	0.25	0.25	0.20	1.00	1.00	1.00	0.33
11	LULC	2.00	5.00	2.00	1.00	0.50	2.00	0.50	2.00	3.00	1.00	1.00	1.00
12	NDVI	2.00	5.00	2.00	0.33	0.33	0.50	0.50	0.50	2.00	3.00	1.00	1.00
	SUM	**20.08**	**55.00**	**23.17**	**5.64**	**12.20**	**11.06**	**7.50**	**9.45**	**29.33**	**31.50**	**10.53**	**16.03**

Table 2. Spatial variables, data sources, sensor types, and classification ranges used in the landfill site suitability analysis for Kadoma City, Zimbabwe

No.	Spatial variable	Source	Sensor type	Categories/Range
1	Soil Type	Harmonized World Soil Database (HWSD)	Derived from Soil Survey/GIS database (No sensor)	Chromic Cambisols, Chromic Luvisols, Ferralic Cambisols, Haplic Lixisols
2	Distance from Built-Up Area (m)	Open Street Map (OSM)	Digitized from OSM (No sensor)	1000–1499, 1500–1999, 2000–2499, 2500–2999, Above 3000
3	Geology	Geological Survey of Zimbabwe	Derived from Geological maps (No sensor)	Basaltic, Dolerites, Metasediments, Granite
4	Distance from Railway Line (m)	Open Street Map (OSM)	Digitized from OSM (No sensor)	250–499, 500–749, 750–999, 1000–1249, Above 1250
5	Distance from Main Rivers (m)	Open Street Map (OSM)	Digitized from OSM (No sensor)	500–999, 1000–1499, 1500–1999, 2000–2499, Above 2500
6	Distance from Main Roads (m)	Open Street Map (OSM)	Digitized from OSM (No sensor)	300–499, 500–749, 750–999, 1000–1199, Above 1200
7	NDVI	Shuttle Radar Topography Mission (USGS)	Sentinel-2 MSI (Multispectral Instrument)	Range: −0.657843 to 0.805328
8	Land Use Land Cover (LULC)	Shuttle Radar Topography Mission (USGS)	Sentinel-2 MSI (Multispectral Instrument)	Bareland, Forest, Built-up Area, Cropland, Grassland
9	Wind Speed (m/s)	WorldClim version 2.1 dataset	WorldClim (Interpolated climatic model, no direct sensor)	Range: 4.21247–6.34718
10	Elevation (m)	Shuttle Radar Topography Mission (USGS)	SRTM DEM (Radar—C-band)	Below 1000, 1000–1040, 1040–1080, 1080–1120, Above 1120
11	Slope (°)	Shuttle Radar Topography Mission (USGS)	SRTM DEM (Radar—C-band, derived)	Below 5, 5–10, 10–15, 15–20, Above 20
12	Distance from Powerlines (m)	Open Street Map (OSM)	Digitized from OSM (No sensor)	100–199, 200–299, 300–399, 400–499, Above 500

DEM dataset. It was reclassified with preference to areas with moderate elevation to minimize runoff risks, and very low or very high elevations were deemed unsuitable. Geology data were obtained from the Geological Survey of Zimbabwe at a scale of 1:250,000. The geological map was digitized and georeferenced in ArcGIS Pro. Rock types that are more impermeable, such as granites, were considered more suitable, while highly permeable formations like sandstones were ranked lower. Soil data were sourced from the Harmonized World Soil Database (HWSD). Soil types were extracted, and their permeability characteristics were evaluated. Less permeable soils (e.g. clayey soils) were considered more suitable for landfill sites, while highly permeable soils were marked unsuitable. The river network was also obtained from Open Street Map and supplemented with hydrographic layers from the Zimbabwe National Water Authority (ZINWA). A Euclidean Distance analysis was performed, and areas within a 500-meter buffer from rivers were considered unsuitable to prevent leachate contamination of water resources. Railway line data were extracted from OSM. Similar to roads, a Euclidean Distance surface was generated, and proximity thresholds were reclassified. While proximity to transport is favorable for landfill operations, very close siting was avoided to minimize operational disruptions. Powerlines were extracted from Open Street Map datasets. Proximity analyses were conducted, but areas directly under or too close to powerlines were deemed unsuitable to avoid interference with infrastructure. The Land Use/Land Cover (LULC) map was classified

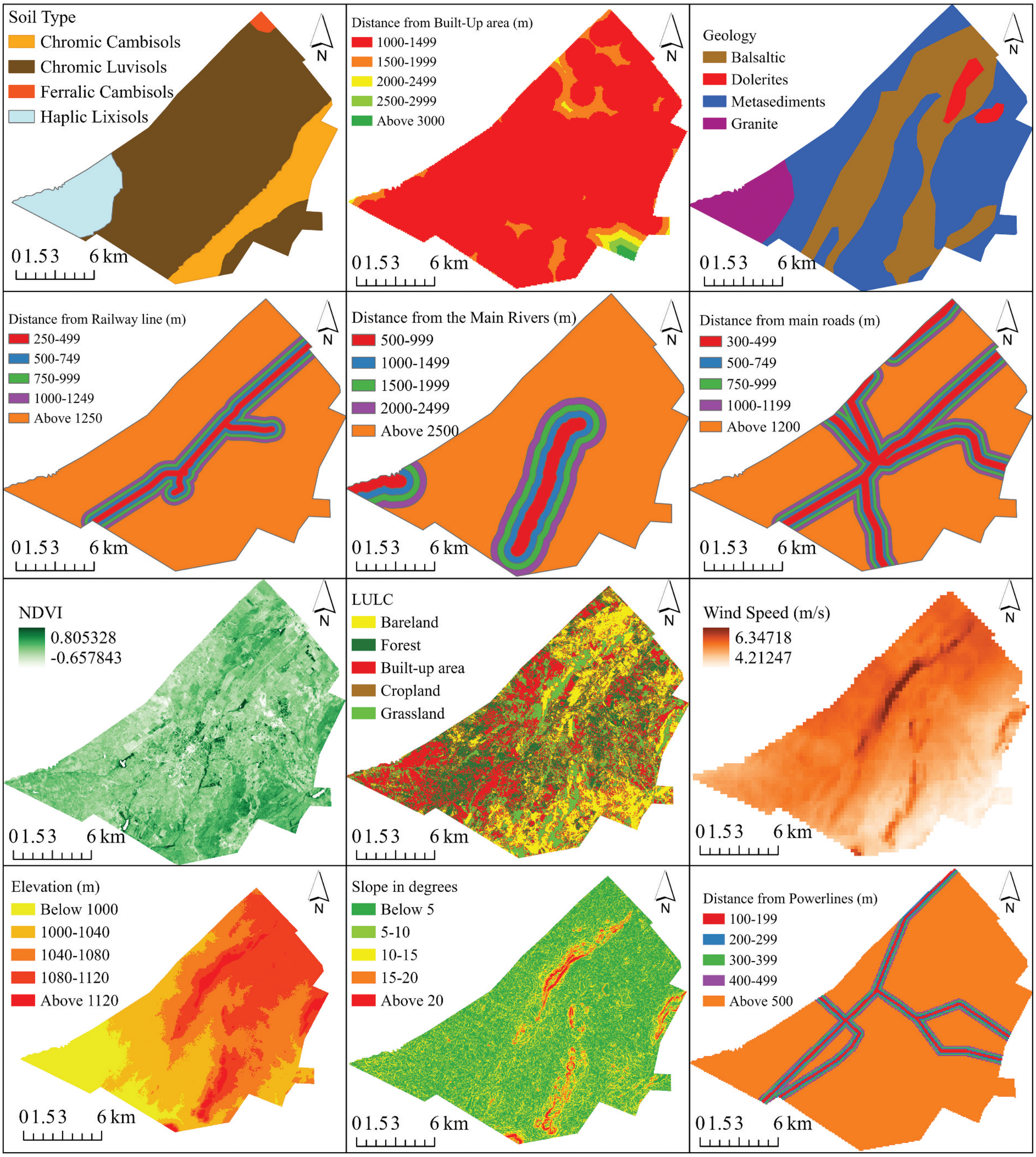

Figure 3. Spatial criteria maps used in the GIS-Based analytical hierarchy process (AHP) for landfill site suitability analysis in Kadoma Municipality, Zimbabwe. This figure illustrates the spatial datasets employed as constraints and evaluation criteria in the AHP-based landfill site suitability modeling for Kadoma Municipality. The 12 thematic layers include: (1) soil type, (2) distance from built-up areas, (3) geology, (4) distance from railway lines, (5) distance from main rivers, (6) distance from major roads, (7) normalized difference vegetation index (NDVI), (8) land use/land cover (LULC), (9) wind speed, (10) elevation, (11) slope, and (12) distance from powerlines. Each layer was derived from geospatial datasets and classified into suitability ranges based on environmental, social, and regulatory considerations. These criteria collectively inform the multi-criteria decision analysis (MCDA) for identifying optimal landfill sites, ensuring that selected locations minimize environmental degradation, avoid ecological sensitivity, and promote sustainable urban waste management in accordance with Zimbabwean environmental guidelines.

from Sentinel-2 imagery. Preprocessing included atmospheric correction and layer stacking, and supervised classification identified urban, agricultural, water, forest, and barren land categories. Urban and forested areas were marked unsuitable, whereas barren lands and grasslands were deemed most suitable. NDVI was computed from Sentinel-2 imagery using the formula (NIR—Red)/(NIR + Red) in the Raster Calculator of ArcGIS Pro. NDVI values were classified into vegetation density categories. Areas with very low NDVI values (indicating sparse or no vegetation) were preferred for landfill siting to minimize ecological disturbance.

All spatial layers were standardized to a common resolution of 30 meters and projected to UTM Zone 35S for consistency. Final thematic layers were weighted and integrated using the Analytical Hierarchy Process based on expert judgment and literature-derived importance scores (Figure 2).

2.4. Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) was employed to determine the most suitable sites for landfill development in Kadoma City, Zimbabwe. AHP is a multi-criteria decision-making method that structures complex problems into a hierarchy (Vaidya & Kumar, 2006), allowing systematic evaluation of various factors based on their relative importance (Vargas, 1990). The process began by defining the goal (Saaty, 2008) (landfill site selection), the criteria (12 spatial factors), and the sub-criteria within each factor (Saaty, 2008).

A key step in AHP is the development of a Pairwise Comparison Matrix (Table 1), where each factor was compared with every other factor to assess its relative importance towards landfill suitability (Brunelli, 2014). Experts in environmental management and GIS were consulted to assign judgments based on the AHP scale values (Table 3) proposed by Saaty (2008), ranging from 1 (equal importance) to 9 (extreme importance of one factor over another). This structured the subjective judgments into a quantifiable form. After completing the pairwise comparisons, a Standardized Matrix (Table 4) was generated by normalizing each column of the pairwise matrix (Saaty, 2008). Each element of the matrix was divided by the sum of its column, ensuring that the influence of each factor was scaled appropriately. The total weight of each factor was then calculated by averaging the values across each row of the standardized matrix, representing the relative contribution of each factor to the landfill suitability model (Zelenović Vasiljević et al., 2012). To verify the consistency of the judgments made in the pairwise comparisons, the Consistency Index (CI) and Consistency Ratio (CR) were calculated (Table 5). The CI was derived using the formula $CI = (\lambda\_max—n)/(n - 1)$, where λ_max is the maximum eigenvalue of the matrix and n is the number of factors (Saaty, 2008; Vaidya & Kumar, 2006; Vargas, 1990). The Saaty's CR values (Table 6) were used as a benchmark, with an acceptable threshold of $CR \leq 0.1$. A CR value below 0.1 indicated that the pairwise comparisons were consistent and reliable (Saaty, 2008); otherwise, the matrix would require revision. Sub-criteria and Classification Ratings (Table 7) were defined for each factor to guide the reclassification of raster datasets. For instance, slope was categorized into suitability classes such as 0–5° (highly suitable) and > 15° (unsuitable). Similarly, distance thresholds were established for roads, rivers, and built-up areas, while NDVI and LULC classes were rated according to their favorability for landfill development. After applying

Table 3. AHP scale values

Scale value	Definition
AHP Scale values	
1	Equal Importance
2	Equal to Moderate importance
3	Moderate importance
4	Moderate to Strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very strong to extremely strong importance
9	Extreme importance

Table 4. Standardized matrix

	Factor	Slope	Wind	Road	Built-up area	Elevation	Geology	Soil	River	Railway line	Powerlines	LULC	NDVI	Weight
Standardized matrix														
1	Slope	0.05	0.07	0.01	0.04	0.08	0.03	0.07	0.11	0.10	0.06	0.05	0.03	**5.9%**
2	Wind	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.01	**1.6%**
3	Road	0.15	0.05	0.04	0.04	0.04	0.03	0.04	0.04	0.03	0.06	0.05	0.03	**5.1%**
4	Built-up area	0.20	0.15	0.22	0.18	0.25	0.18	0.27	0.11	0.17	0.16	0.09	0.19	**17.9%**
5	Elevation	0.05	0.09	0.09	0.06	0.08	0.09	0.07	0.05	0.10	0.10	0.19	0.19	**9.6%**
6	Geology	0.15	0.13	0.13	0.09	0.08	0.09	0.13	0.05	0.07	0.13	0.05	0.12	**10.2%**
7	Soil	0.10	0.11	0.13	0.09	0.16	0.09	0.13	0.21	0.14	0.13	0.19	0.12	**13.4%**
8	River	0.05	0.11	0.13	0.18	0.16	0.18	0.07	0.11	0.14	0.16	0.05	0.12	**12.1%**
9	Railway line	0.02	0.05	0.04	0.04	0.03	0.05	0.03	0.03	0.03	0.03	0.03	0.03	**3.4%**
10	Powerlines	0.02	0.04	0.02	0.04	0.03	0.02	0.03	0.02	0.03	0.03	0.09	0.02	**3.4%**
11	LULC	0.10	0.09	0.09	0.18	0.04	0.18	0.07	0.21	0.10	0.03	0.09	0.06	**10.4%**
12	NDVI	0.10	0.09	0.09	0.06	0.03	0.05	0.07	0.05	0.07	0.10	0.09	0.06	**7.1%**

Table 5. Consistency index and consistency ratio worksheet

	Factor	Slope	Wind	Road	Built-up area	Elevation	Geology	Soil	River	Railway line	Powerlines	LULC	NDVI	SUM	SUM/ Weight
Consistency index & Consistency ratio worksheet															
1	Slope	0.06	0.07	0.02	0.04	0.10	0.03	0.07	0.12	0.10	0.07	0.05	0.04	**0.76**	**12.86**
2	Wind	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.01	**0.21**	**12.90**
3	Road	0.18	0.05	0.05	0.04	0.05	0.03	0.04	0.04	0.03	0.07	0.05	0.04	**0.67**	**13.16**
4	Built-up area	0.24	0.13	0.25	0.18	0.29	0.20	0.27	0.12	0.17	0.17	0.10	0.21	**2.34**	**13.04**
5	Elevation	0.06	0.08	0.10	0.06	0.10	0.10	0.07	0.06	0.10	0.10	0.21	0.21	**1.25**	**13.02**
6	Geology	0.18	0.11	0.15	0.09	0.10	0.10	0.13	0.06	0.07	0.13	0.05	0.14	**1.32**	**12.99**
7	Soil	0.12	0.10	0.15	0.09	0.19	0.10	0.13	0.24	0.14	0.13	0.21	0.14	**1.75**	**13.07**
8	River	0.06	0.10	0.15	0.18	0.19	0.20	0.07	0.12	0.14	0.17	0.05	0.14	**1.57**	**12.99**
9	Railway line	0.02	0.05	0.05	0.04	0.03	0.05	0.03	0.03	0.03	0.03	0.03	0.04	**0.44**	**12.84**
10	Powerlines	0.03	0.03	0.03	0.04	0.02	0.03	0.03	0.02	0.03	0.03	0.10	0.02	**0.42**	**12.51**
11	LULC	0.12	0.08	0.10	0.18	0.05	0.20	0.07	0.24	0.10	0.03	0.10	0.07	**1.35**	**13.02**
12	NDVI	0.12	0.08	0.10	0.06	0.03	0.05	0.07	0.06	0.07	0.10	0.10	0.07	**0.92**	**12.94**
count								12.00							
lambda max								12.945							
CI								0.086							
CR								**0.06**							
constant								1.49							

Table 6. Saaty's CIr values for matrices

Size of matrix	Random consistency (CIr)	
Saaty's CIr values for matrices are given by the following table		
1	0	1
2	0	2
3	0.58	3
4	0.90	4
5	1.12	5
6	1.24	6
7	1.32	7
8	1.41	8
9	1.45	9
10	1.49	10

the standardized weights and classification ratings, a Suitability Index map was produced. The study further analyzed the Area Coverage of Suitability Indexes (Table 8), categorizing the land into different suitability classes (e.g. highly suitable, moderately suitable, unsuitable) and quantifying the spatial extent of each category within Kadoma City.

The final landfill suitability map (Figure 4) was generated by overlaying all weighted layers through a weighted linear combination method in ArcGIS Pro 3.0, resulting in a comprehensive, spatially explicit output for informed landfill site selection.

3. Results

The pairwise comparison matrix for landfill site selection in Kadoma City, Zimbabwe, shows the relative importance of twelve spatial factors using AHP (Table 1). Built-up area, geology, and soil were ranked highly important, with built-up area having consistently higher values against other factors, indicating strong influence in siting decisions. Conversely, wind, railway lines, and power-lines had generally lower values, suggesting they were less critical. Factors like slope, road, elevation, and river displayed moderate importance. The 'SUM' row at the bottom indicates the total of each column, which was later used for standardizing the matrix to compute final factor weights for suitability analysis.

The standardized matrix (Table 3) for landfill site selection in Kadoma City, Zimbabwe, shows the normalized importance of each factor across all comparisons. Built-up area had the highest weight at 17.9%, highlighting it as the most influential factor, followed by soil (13.4%), river (12.1%), and geology (10.2%). Factors like wind (1.6%), railway lines (3.4%), and powerlines (3.4%) had the least influence. The weights were derived by averaging each row across all standardized values. These weights were then used in the weighted overlay analysis to create the final landfill suitability map, ensuring that more critical factors had greater impact on site selection.

The Consistency Index and Consistency Ratio worksheet (Table 5) for landfill site selection in Kadoma City evaluates the reliability of judgments made in the pairwise comparisons. Each factor's SUM/Weight value was calculated, showing how consistent each comparison was relative to the assigned weight. The average of all SUM/Weight values approximated the maximum eigenvalue (λ_max). From this, the Consistency Index (CI) and Consistency Ratio (CR) were computed. A CR less than 0.1 confirmed that the comparisons were acceptably consistent. Thus, the prioritization of factors like built-up area, soil, and river in the AHP process was statistically reliable for producing the landfill suitability map.

The Sub-Criteria and Classification Rating table for landfill site selection (Table 7) in Kadoma City, Zimbabwe, defines how each spatial factor was reclassified into a suitability index based on specific conditions. For rivers, areas within 500 meters were considered highly unsuitable, while distances greater than 2000 meters were rated highly suitable. Slope was rated highest (5) for gentle slopes below 5°, while slopes above 20° were highly unsuitable. Elevation followed a similar pattern, with lower elevations (1073-–1130 m) rated highly suitable. Wind speeds between 4.2 and 5 m/s were deemed suitable, while speeds above 5 m/s were moderately suitable. Proximity to built-up areas and roads also influenced suitability: areas closer than 1000 m to built-up areas and 300 m to roads were highly unsuitable, while distances greater than 2500 m and 900 m, respectively, were considered more favourable. Geology favoured stable rock formations like dolerites and granites, while soil types like Chromic Luvisols were highly suitable. Proximity to railway lines and power lines followed distance-based ratings, where larger buffers increased suitability. For Land Use Land Cover (LULC), bare lands were highly suitable, and built-up areas were highly unsuitable. NDVI values indicating bare land were most favourable, while dense vegetation indicated unsuitable sites.

The total weight of factors (Table 8), derived through the AHP method, showed that the built-up area was the most influential criterion with a weight of 17.9%, emphasizing the need to avoid densely populated zones. Soil type (13.4%), river proximity (12.1%), and geology (10.2%) also carried significant influence, reflecting environmental safety priorities. Lesser weights were assigned to factors like wind speed (1.6%), railway lines, and power lines (both 3.4%). These results guided the identification of optimal landfill sites while balancing environmental, infrastructural, and social considerations.

The area coverage analysis of suitability indexes (Table 8) for landfill site selection in Kadoma City, Zimbabwe, revealed that a vast majority of the land, about 90% (25,067 hectares), was classified as highly unsuitable. Only a small portion was identified as moderately suitable (4.8%, covering 1,208 hectares) and suitable (5.2%, covering 1,425 hectares), indicating limited ideal locations for landfill development. Focusing on potential suitable sites (Figure 5), Site A emerged as the largest and most promising, covering 722 hectares, which accounts for 50.6% of the total suitable area. It was followed by Site B at 30.4%, and Site C at 13.2%, while the remaining sites (D, E, F, and G) each represented less than 3% individually.

Table 7. Sub-criteria and classification Rating

Criterion	Exclusionary criteria	Suitability index	Scale value
Sub–Criteria and Classification Rating			
Rivers	Below 500 m	Highly unsuitable	0
	500–1000 m	Unsuitable	2
	1000–1500 m	Moderately suitable	3
	1500–2000 m	Suitable	4
	Above 2000 m	Highly suitable	5
Slope	Below 5°	Highly suitable	5
	5–10°	Suitable	4
	10–15°	Moderately suitable	3
	15–20°	Unsuitable	2
	Above 20°	Highly unsuitable	1
Elevation	1073–1130 m	Highly suitable	5
	1130–1150 m	Suitable	4
	1150–1180 m	Moderately suitable	3
	1180–1200 m	Unsuitable	2
	Above 1200 m	Highly unsuitable	1
Wind speed	4.2–5	Suitable	4
	5–6	Moderately suitable	3
	> 6	Moderately suitable	3
Built–up area	Below 1000 m	Highly unsuitable	0
	1000–1500 m	Unsuitable	2
	1500–2000 m	Moderately suitable	3
	2000–2500 m	Suitable	4
	Above 2500 m	Highly suitable	5
Roads	Below 300 m	Highly unsuitable	0
	300–500 m	Unsuitable	2
	500–700 m	Moderately suitable	3
	700–900 m	Suitable	4
	Above 900 m	Moderately suitable	3
Geology	Dolerites and gabbros	Highly suitable	5
	Older Gneiss Complex	Suitable	4
	Metasediments, felsic metavolcan	Moderately suitable	3
	Balsaltic metavolcanics	Highly suitable	5
	Younger intrusive granite	Highly suitable	5
Soil Type	Ferralic Cambisols	Unsuitable	2
	Chromic Luvisols	Highly suitable	5
	Chromic Cambisols	Unsuitable	2
	Haplic Lixisols	Moderately suitable	3
Railway line	Below 250 m	Highly unsuitable	0
	250–500 m	Unsuitable	2
	500–750 m	Moderately suitable	3
	750–1000 m	Suitable	4
	Above 1000 m	Highly suitable	5
Power lines	Below 100 m	Highly unsuitable	0
	100–200 m	Unsuitable	2
	200–300 m	Moderately suitable	3
	300–400 m	Suitable	4
	Above 400 m	Highly suitable	5
LULC	Bare land	Highly suitable	5
	Built–up area	Highly unsuitable	0
	Forests	Unsuitable	2
	Grasslands	Moderately suitable	3
	Cropland	Unsuitable	2
NDVI	−0.6578 – −0.0151 (No vegetation)	Moderately suitable	3
	−0.0151–0.2143 (Bare land)	Highly suitable	5
	0.2143–0.2717 (Bare land/sparse vegetation)	Moderately suitable	3
	0.2717–0.3462 (Sparse vegetation)	Moderately suitable	3
	0.3462–0.8053 (Scattered vegetation/Forest)	Highly unsuitable	0

4. Discussion

The landfill site selection results for Kadoma City, Zimbabwe, highlight both the opportunities and significant constraints facing sustainable waste management in a rapidly urbanizing environment. Our analysis, based on a GIS-integrated Analytical Hierarchy Process (AHP) and Multi-Criteria Evaluation (MCE), provided an in-depth understanding of the spatial limitations and potentials for landfill

Table 8. Area Coverage of suitability Indexes and the total weight of factors

Suitability index	Area (Ha)	Area (%)
Area Coverage of Suitability Indexes		
Highly Unsuitable	25067	90
Moderately suitable	1208	4.8
Suitable	1425	5.2
Site	Area (Ha)	Area (%)
Area Coverage of Potential Suitable Sites		
Site A	722	50.6
Site B	434	30.4
Site C	188	13.2
Site D	38.9	2.7
Site E	16.6	1.2
Site F	13.6	1
Site G	12.7	0.9
Factor	Eigenweight vector	Weight (%)
Total weight of factors		
Slope	0.059	5.9
Wind speed	0.016	1.6
Main road	0.051	5.1
Built-up area	0.179	17.9
Elevation	0.096	9.6
Geology	0.102	10.2
Soil type	0.134	13.4
River	0.121	12.1
Railway line	0.034	3.4
Power lines	0.034	3.4
LULC	0.104	10.4
NDVI	0.071	7.1

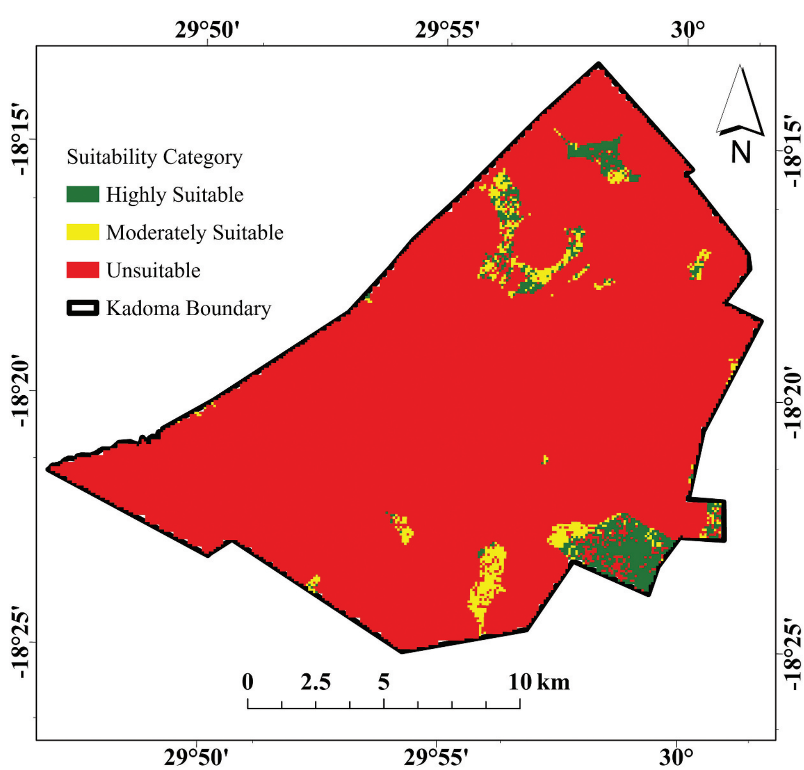

Figure 4. Final landfill site suitability map for Kadoma City derived from GIS-Based Analytical Hierarchy process (AHP) multi-criteria evaluation. This map presents the final landfill site suitability assessment for Kadoma City, Zimbabwe, following the integration of 12 spatial decision-making criteria through the GIS-based Analytical Hierarchy process (AHP). The suitability levels are classified into three categories: highly suitable (green), moderately suitable (yellow), and unsuitable (red), delineated within the official administrative boundary of Kadoma (black outline).

development. Rather than simply reiterating earlier classifications, this discussion critically interprets the key findings, explores their implications for urban planning, compares results with similar studies, examines multi-criteria trade-offs, and outlines the practical and ethical considerations arising from the proposed sites. The pairwise comparison process revealed that built-up area (17.9%), soil (13.4%), river proximity (12.1%), and geology (10.2%) were the most influential factors in landfill site selection. Built-up areas particularly stood out, receiving the highest weight, reflecting the need to avoid densely populated zones to minimize health risks and land use conflicts. Conversely, wind speed (1.6%), railway lines (3.4%), and power lines (3.4%) were considered less critical. Importantly, the Consistency Ratio (CR) was below 0.1, confirming that the factor prioritization was reliable and consistent, enhancing the methodological robustness of the study.

The spatial analysis yielded a striking finding: approximately 90% of Kadoma's land area was classified as highly unsuitable for landfill development. Only 4.8% (1,208 hectares) was moderately suitable, and 5.2% (1,425 hectares) was suitable. Among the suitable sites, Site A, covering 722 hectares, emerged as the most promising, and accounting for 50.6% of all suitable land, followed by Sites B and C. This significant restriction in available land underscores the growing challenge of accommodating waste infrastructure within the existing urban and peri-urban fabric (Abujayyab et al., 2015). The high restriction percentage was largely expected given Kadoma's urban expansion and ongoing land use intensification. However, the extent of unsuitability—spanning over 90% of the city's area—was even more severe than initially anticipated, signalling that future waste management planning must be highly strategic and proactive. In interpreting these findings, it is clear that Kadoma faces critical pressures typical of rapidly urbanizing cities in Africa. The scarcity of suitable sites necessitates careful balancing between environmental protection, public health, and urban growth imperatives (Shukor et al., 2024). Urban waste management strategies must now be tightly integrated with broader land use planning to avoid exacerbating land scarcity problems (Ali & Ahmad, 2020). The prominent influence of built-up areas confirms the need to enforce stringent setbacks from residential zones, while the significant weight assigned to soil type, geology, and river proximity reflects environmental risk mitigation priorities, especially regarding groundwater contamination and surface water protection.

Comparing our results with similar studies conducted in other urbanizing areas reveals important parallels and divergences. For instance, studies in Nairobi, Kenya (Adegun, 2017; Knowledge, 2016) and in Kumasi, Ghana (Mensah, 2020; Odom et al., 2021) also found that over 85% of city areas were unsuitable for landfill development due to urban encroachment and environmental constraints. However, our study identified a slightly higher percentage of unsuitable land, suggesting that Kadoma's land use dynamics may be even more restrictive than regional counterparts. Furthermore, whereas other studies often found transportation networks to be major influencing factors, in Kadoma, proximity to roads, railway lines, and power lines played a comparatively lesser role. This divergence can be attributed to Kadoma's specific urban form and existing infrastructural distribution, highlighting the necessity of localized, context-sensitive waste planning approaches. A critical reflection on the interaction among criteria also offers valuable insights. The moderate weights assigned to slope, elevation, roads, and rivers illustrate how multiple moderately favourable or unfavourable conditions can cumulatively determine overall site suitability. For instance, a location with a gentle slope and acceptable elevation but situated close to a river or within a high-density built-up area could be rendered unsuitable despite meeting some favourable criteria (Rahmat et al., 2017). This underscores the strength of AHP and MCE in capturing the complex trade-offs involved in real-world decision-making and the non-linearity of spatial suitability analysis (Wang et al., 2009). It also highlights the difficulty of identifying 'perfect' sites, necessitating compromise and prioritization among competing objectives (Zelenović Vasiljević et al., 2012). The relationship between the identified suitable sites and existing municipal land use plans is another critical dimension. Preliminary overlay analysis suggests that some suitable sites, particularly Site A, fall partially outside currently designated waste zones and may overlap with agricultural lands or peri-urban settlements. This mismatch points to potential land tenure conflicts, especially if sites are located on privately owned or communally used lands. Municipal planners must therefore be prepared to negotiate land acquisition, compensation, or land-use re-zoning, informed by both technical assessments and participatory planning processes. The results provide an evidence base that can be used to update zoning plans, strengthen waste infrastructure strategies, and integrate waste facility siting more effectively into Kadoma's broader urban development framework.

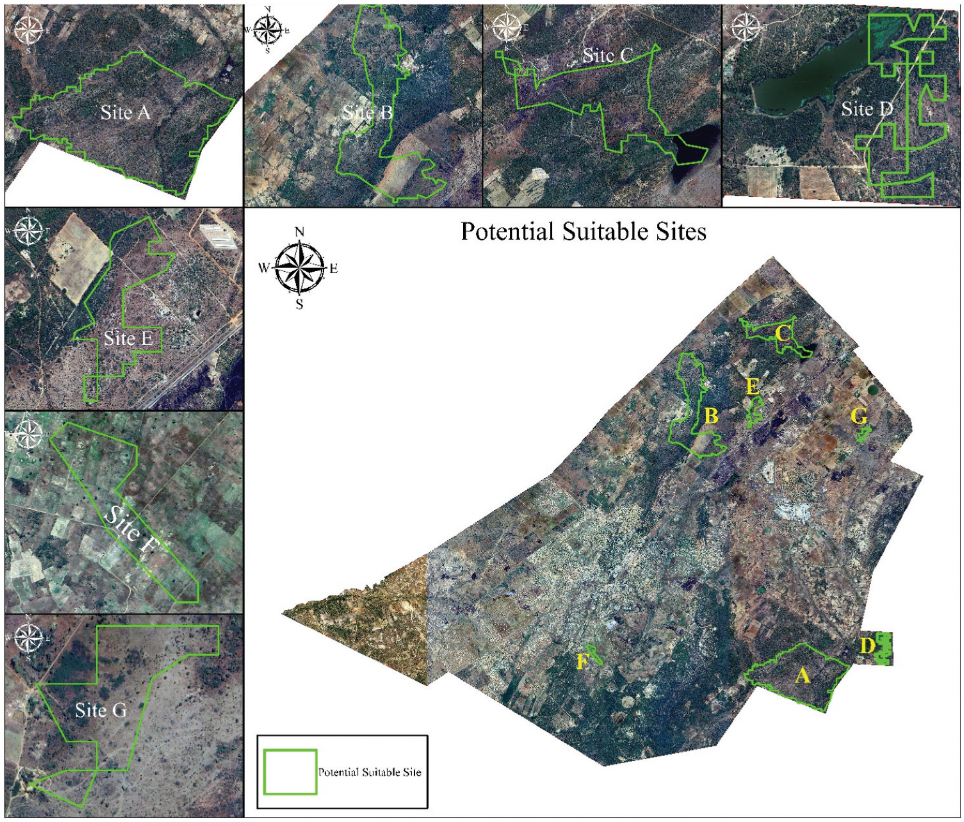

Figure 5. Aerial visualization of potential suitable sites.

Another key consideration is the social and ethical dimension of landfill siting. Communities located near the proposed sites are likely to be the most affected, both in terms of potential environmental externalities and changes in land use. It is critical that any movement toward final site selection be accompanied by comprehensive community consultations, social impact assessments, and participatory decision-making processes. Early and transparent engagement with affected communities can help build trust, identify concerns, and co-develop mitigation strategies, thereby aligning waste management initiatives with principles of good governance and social equity. Despite the methodological strengths of this study, several limitations warrant acknowledgment. First, although AHP provides a systematic framework for weighting factors, the assignment of relative importance remains partly subjective, influenced by the research team's expert judgment and literature precedents. In future work, incorporating broader expert stakeholder input—such as urban planners, environmental scientists, and local authorities—would enhance the validity and inclusivity of weight assignments. Second, the study relied on high-resolution satellite imagery and spatial datasets, which, while sufficient for a city-wide analysis, may mask finer-scale variations in land characteristics. Fine scale data from LiDAR (Light detection and ranging)—and detailed ground surveys could refine the analysis and better capture micro-level suitability nuances. Third, some base maps, particularly for roads and built-up areas, may be outdated given Kadoma's rapid expansion. Regular updates to geospatial databases and systematic ground-truthing efforts are essential to ensure that landfill siting decisions are based on the most current information. Beyond these limitations, actionable recommendations arise from this study. We propose that Site A and Site B be prioritized for detailed Environmental Impact Assessments (EIA), including hydrogeological investigations, biodiversity surveys, and community risk assessments. The EIA process should be participatory and transparent, ensuring that environmental and social risks are thoroughly evaluated before final site selection. Moreover, we recommend institutionalizing GIS-AHP methodologies within Kadoma's municipal waste management frameworks. Building capacity among municipal staff for GIS-based multi-criteria evaluation would support more evidence-based, adaptive planning and reduce reliance on ad-hoc, politically influenced site selection processes. It is also important to emphasize that identifying suitable sites represents only the initial phase of the landfill development process. Numerous practical and institutional obstacles could delay or complicate site implementation. For instance, land acquisition disputes, financial constraints, regulatory hurdles, and public opposition are all potential barriers. To mitigate these risks, we recommend a phased implementation strategy starting with stakeholder dialogues, preliminary site visits, and feasibility studies assessing technical, economic, and social viability. Securing early buy-in from political leaders, civil society groups, and community representatives will be crucial for successful project advancement.

In general, this study demonstrates that while Kadoma City has limited spatial options for landfill development due to high urbanization and environmental constraints, systematic GIS-AHP methods can effectively identify and prioritize viable sites. The findings not only contribute to local waste management planning but also add to the growing body of evidence supporting the applicability of GIS-based multi-criteria decision analysis in rapidly urbanizing, data-scarce contexts across Africa. Going forward, integrating technical analyses with community engagement, policy alignment, and institutional capacity building will be essential for translating spatial suitability maps into sustainable, equitable, and operational waste management solutions.

5. Conclusion

This study demonstrated that the GIS-integrated Analytical Hierarchy Process (AHP) effectively identified limited but viable landfill sites in Kadoma City, balancing environmental safety, public health, and infrastructure considerations. Key findings revealed that over 90% of the land was unsuitable, highlighting severe land scarcity challenges driven by urban expansion. While the approach offers valuable spatial guidance, it relied on secondary datasets without recent land use validation or stakeholder input, suggesting the need for updated analyses. The identified sites, particularly Site A and Site B, should undergo detailed environmental and socio-economic impact assessments before implementation to ensure long-term sustainability. Moreover, future applications of this model should be integrated with participatory stakeholder consultations to promote public acceptance and administrative feasibility. The GIS-AHP framework demonstrated here can be adapted and scaled to support landfill planning in other rapidly urbanizing cities across Zimbabwe and Sub-Saharan Africa, where land pressures and waste generation trends mirror Kadoma's context. By combining spatial analysis with inclusive planning processes, cities can better address the complex challenges of sustainable waste management.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

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