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Site Suitability Analysis for Waste to Energy Facility in Jos Metropolis, Plateau State, Nigeria

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Abstract

Solid waste management has emerged as a significant environmental challenge in developing countries, primarily driven by population growth, rapid urbanization, and the absence of effective sustainable strategies and policies. The city of Jos is not immune to these issues, as limited funding and expertise have hindered the local municipalities' ability to manage municipal solid waste efficiently. This study attempted to identify suitable sites for a waste-to-energy facility in Jos Metropolis, Plateau State, Nigeria. The study focused on estimating the amount of waste generated and determining a suitable site for siting a waste-to-energy facility in the study area. The data used were geographic coordinates of existing dumpsites which were acquired using Garmin eTrex R 20x Handheld GPS, topographic map which was obtained from Landsat (Glovis) website, landuse/landcover map which was obtained from Sentinel-2 ESRI website, road and waterbody data which were obtained from Open Street Map and administrative map of Jos metropolis which was obtained from ministry of lands, survey and town planning, Plateau state. Multi-criteria analysis, waste estimation formula, population projection formula, and the Analytic Hierarchy Process (AHP) in conjunction with a Geographic Information System (GIS) model were employed for analysis. The results revealed that an estimated 221 tons of waste is generated per day in Jos metropolis with a projected increase to 299 tons by 2032, reflecting a 35.29% growth in a decade. The multicriteria analysis revealed that only 2.8% (23.3 km²) of the area exhibited high suitability for a WtE facility, with Kuru 'A' identified as the optimal choice due to its advantageous proximity to power substations, well-established road networks, existing dumpsites, and minimal risks to people and economic activities. Based on the findings, the study recommends improving data collection efforts, expanding the suitability criteria, and involving stakeholders in decision-making processes to enhance waste management effectiveness.

Keywords: Solid Waste Management; Waste-to-Energy; Geographic Information System; Analytic Hierarchy Process

INTRODUCTION

Municipal solid waste (MSW) management has become a growing global concern due to its potential impacts on the environment, public health, and social well-being. According to the World Health Organization (WHO), over 2 billion tons of MSW are generated annually, with a projected increase to 3.4 billion tons by 2050 (WHO, 2021). Moreover, African municipal authorities are unable to handle this fast-growing municipal waste, resulting in waste disposal as one of the most prominent environmental problems (Dung-Gwom & Musa, 2018). Therefore, the ability to provide solutions on how to manage the large quantities of waste

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generated is one of the major challenges facing current and future generations (World Energy Council, 2016).

MSW management can be done through a variety of methods such as landfill, incineration, recycling, and composting (Hollins *et al.*, 2017). This is especially pertinent in developing countries such as Nigeria, where waste management is one of the greatest environmental challenges (Kannangara *et al.*, 2018; Aderoju & Guerner, 2020). SWM has both environmental and economic impacts (Varjani & Upasani, 2021). Mismanaged MSW causes choking of Rivers, blockage of sewers, and drainage networks, which can lead to flooding (Hossain *et al.*, 2021), with remediation requiring hefty monetary investments (Adesra *et al.*, 2021). In contrast, developed countries are increasingly turning to sustainable waste management practices such as reducing waste at the source, implementing treatment and reuse methods, and utilizing WtE technologies to produce heat and electricity (Khalil *et al.*, 2019). However, many developing countries still fail to meet basic safe waste collection and disposal standards, due to factors such as population growth, inward migration, and rising living standards (Ahmed & Suryabhagavan, 2021; Abushammala *et al*., 2022).

Establishing an incineration plant to reduce Municipal Solid Waste (MSW) decreases the waste volume and alleviates the associated disposal costs (Hassaan, 2015). Moreover, the simultaneous generation of energy through Waste-to-Energy (WtE) makes it an appealing option for waste management (Nabavi-Pelesaraei et al., 2017). However, selecting an appropriate site for a WtE facility is a crucial step that necessitates the consideration of important economic, environmental, technical, and social criteria (Wu et al., 2018). In this regard, Geographic Information System (GIS)-based Multi-Criteria Analysis (MCA) has been extensively employed in solid waste management and site suitability analysis, as demonstrated by recent studies conducted by Abushammala et al. (2022) and Adegbite et al. (2020).

Jos Metropolis, the capital of Plateau State in Nigeria, has experienced rapid population growth, urbanization, and energy demand over the past few years. With the population projected to increase to 2.7 million by 2025, there is an urgent need for an effective waste management strategy. Plateau Environmental Protection and Sanitation Agency (PEPSA) is the waste management agency authorized to collect and dispose of solid waste (SW) in Jos metropolis. However, the current system adopted by PEPSA is inadequate and the existing dumpsite locations cannot be backed by any scientific approach. This has resulted in the illegal dumping of wastes near water bodies, settlements, and roadsides, causing environmental degradation, CO2 emission, air pollution, and adverse effects on human health.

This study conducts site suitability analysis for WtE facilities to provide an efficient waste management system and a sustainable alternative energy source and increase the energy supply mix in the area. The objectives of this study include quantifying the amount of waste generated in the study area and identifying suitable sites for WtE facilities. Through GIS-based Multi-Criteria Analysis (MCA), this study seeks to identify a suitable site for a WtE facility in the study area, thereby reducing the illegal dumping of waste that leads to environmental degradation, CO2 emission, air pollution, and adverse effects on human health.

MATERIAL AND METHODS

Study Area

Jos Metropolis is Plateau State's capital in Nigeria's middle belt region. It lies between Latitudes 9°34'33''N to 10°04'38''North of the Equator and Longitudes 8°35'30''E to

9°06'00''East of the Greenwich Meridian (Figure 1) and it covers a total land area of about 841 km^2 (Fola Consult, 2009).

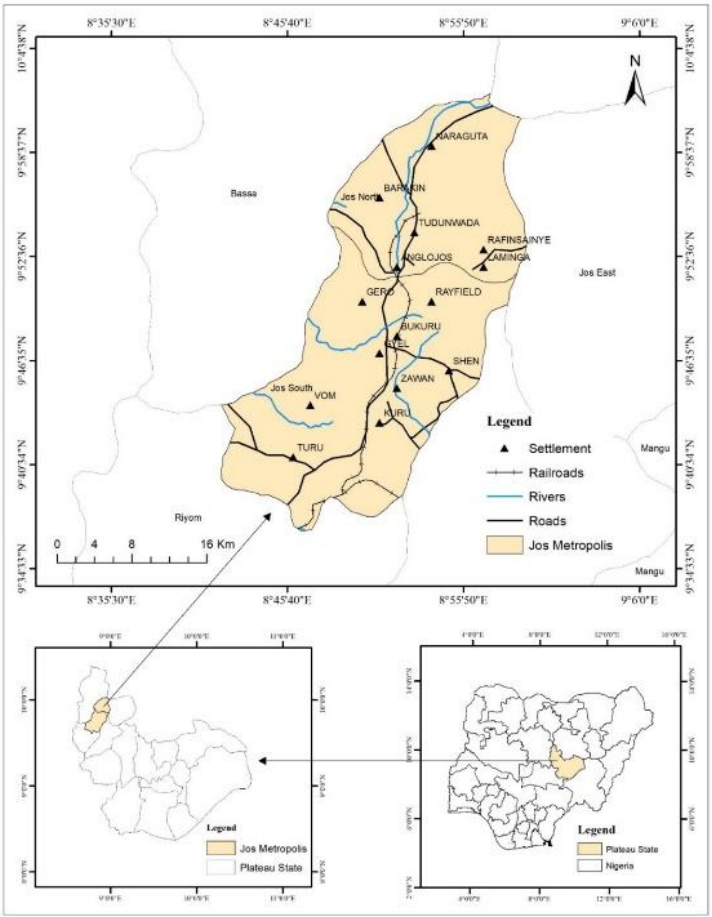

Figure 1: Jos Metropolis
Source: Adapted from the Administrative map of Plateau State (2022)

The study area shares a boundary with Bassa LGA and part of Bauchi State to the North, Jos-East LGA to the east, Riyom LGA to the South-West, and Barkin Ladi LGA to the South-East (Plateau State Ministry of Lands, Survey, and Town Planning). The climate of the study area is characterized by two distinct seasons (wet and dry). The rainy season is between April and October while the dry season is between November and March. The annual rainfall is 1524mm with a mean annual rainfall of 127mm, and the wettest month of the year is July and August (Bitrus, 2014)
.

The temperature ranges between 11^{o}C during the harmattan to 31^{o}C during the peak of the rainy season. The mean temperature is 22^{o}C. The Jos Plateau covers a landmass of about 8600 km^2 and is bounded by 300-600 meters of escarpments around much of its circumference. It has an average altitude of 1280 meters above sea level and several granite hill ranges that can reach heights of over 1900 meters.

Jos Metropolis also falls within the northern Guinea savanna zone due to its peculiar location and high altitude. This vegetation zone is characterized by open woodland with tall trees and mainly short grasses at the summit. These form the leguminous woodland savannah and shrubland with rolling topography and extended views. In addition, It has witnessed a high rate of urban growth of 5.5% per annum (NPC, 2010). With a 2022 population projection of 1,948,702 from the estimated 2006 population of 1,300,000 with a growth rate of 2.53 (NPC,

2010) and generating 0.48 to 0.56 kg of municipal solid waste per person per day (World Bank, 2012).

Methodology

Data sets

The various data needed for the research were provided by a multitude of sources. Data from primary field elevation, observation, and secondary sources were collected as shown in Table 1. Peter (2016) projected a 0.5 kg/capita/day waste generation in Jos for 2025 with a 2.7 million predicted population at a 2.99% population growth rate.

Sentinel-2 data of 2022 having a resolution of 10m extracted from the ESRI Living Atlas was used to prepare the land-use/land-cover thematic map. Shuttle Radar Topographic Mission (SRTM) digital elevation data of 30 m resolution were used to generate this study's slope and elevation maps. In the field, a Garmin eTrex R 20x Handheld GPS Receiver with an accuracy of at least 5 meters was used to collect the points of the existing solid waste dump sites. Open Street Map was used to generate the road and water body features. In addition, an accuracy assessment was carried out to verify the area's current land-use/land-cover types to compare with the LULC analysis. All input datasets were projected to WGS 1984 UTM Zone 32N coordinate system.

Methods

To estimate the amount of waste generated in the study area, the following equations described in Table 2 were employed:

Table 2: Waste Estimation Formulas

S/N	Equation	*Definition of parameters*	**Source**
(1)	$GRW = \frac{(Q_s \times 1000)}{(P \times 365)}$	*GRW* = Present generation rate of solid waste (kg/capita/day), Q_s = Quantity of solid waste for the year 2022 (kg), and P = Projected Population of Jos for the year 2022.	Dotson, 2018
(2)	$P_o = P_n + (P_n \times \frac{1+r}{100})n$	P_O = Population at the future date 2022 P_n = Base year population (1991) r = growth rate n = number of intermediary years (1991 – 2022)	Newman, 2001

Shapefiles were created in the Arc-Catalog environment with the same coordinate system as the map. The shapefiles were imported into the ArcMap environment where on-screen digitizing was carried out on scanned images of the study area. The following themes were available among others: roads, dump sites, and ward boundaries, which were also used subsequently for result presentations. This process was undertaken to ensure that all geographic features needed for analysis are in their original location. To identify the suitable areas for WtE facility in the study area, thematic layers of surface water/river, land use/land cover, road network, dumpsites, power substation, and slope maps were integrated using the Weighted Index Overlay Analysis method.

Distance to Roads: the road layer was acquired from OpenStreetMap. Buffer zones for highly suitable, suitable, moderately suitable, least suitable, and unsuitable areas were generated for the roads using Multiple Ring Buffer Analysis tool (Figure 3).

The output was then reclassified with distances between 1000 – 2000m as highly suitable, 2001-3000m, 3001-4000m, and 4001-5000m distance as suitable, moderately suitable, and least suitable respectively. Distances above 5000m as unsuitable were chosen to determine the best sites for the construction of the WtE facility.

Distance to a water body: The water bodies were generated from OpenStreetMap. A buffer zone of more than 1200m from any water body boundary was adopted to protect surface water from contamination using the standards of Abushammala *et al.,* 2022. The ArcGIS 10.8 environment was used to perform this operation of buffering and reclassification in which far buffers are more suitable while closer buffers are unsuitable sites for locating a WtE facility (Figure 3)

Distance to substations: the distance to substations was generated from point shapefile data. The ArcGIS 10.8 environment was used to perform this operation by importing the data acquired from the Grid3 database into the ArcGIS 10.8 environment using the add data tool. Raster buffers were generated for the existing substations using the Multiple Ring Buffer Analysis tool, then reclassified using reclassify tool and the results were used on the weighted overlay analysis (Figure 3).

Land Cover: Landcover - Sentinel-2 10m was extracted from the ESRI Living Atlas. It is important for analysis for the prevention of conflicts with existing land uses. built-up areas, bare land, vegetation areas, and water bodies were completely categorized for analysis (Figure 3). The LULC types of interest in this study are presented in Table 1. Bare lands were prioritized in this study and the result was then used on the weighted overlay analysis.

Table 1: LULC Classification Scheme

S/N	Classes	Description
1	Built-up areas	Residential Commercial, Industrial, and Healthcare facilities
2	Bare land	Exposed soils, and areas of active excavation and production
3	Vegetation	Any species of plants (flora), forest
4	Water Bodies	Rivers, lakes, and reservoirs

Source: Adapted and Modified from Jensen (1986)

Slope: the slope of the study area was generated (Figure 3) from Digital Elevation Model (DEM) using the spatial analyst extension of the surface tool in the ArcGIS 10.8 environment. The thematic slope map was then reclassified into three classes of slope degrees. The reclassified slope was ranked from 1 to 9. With 9 as highly suitable (lower slope), 5 as moderately suitable, and 1 as unsuitable (higher slope) for site selection.

The site suitability map for the WtE facility was acquired by using MCA and layers created to yield a single output map or index of evaluation. Table 2 represents the criteria adopted for analyzing and determining a potential WtE facility.

Table 2: Criteria for the Selection of Waste to Energy Sites in the Study Area

Criteria	Highly suitable	Moderately suitable	Unsuitable	Source
Dumpsite/Landfill	< 1000m	2001 – 3000m	> 4000m	Adegbite *et al* (2020)
Distance to road	1000 – 2000m	3001 – 4000m	> 5000m	Mipun (2015)
Distance to a water body	> 1200m	601 – 900m	< 300m	Abushammala *et al* (2022)
Slope	0^0 - 5^0	5.1^0 - 15^0	> 15^0	Abushammala *et al* (2022)
Substation	< 2500m	5001 – 7500m	> 10000m	Adegbite *et al* (2020)
Soil type	Sandy_Loam	Sandy_Clay_Loam	Loam	Aderoju *et al* (2018)
Landuse/landcover	Bare surfaces	Vegetation/ Buildup area	Water bodies	NESREA (2007); Ghoutum *et al* (2020)

Weight determination: The relative weight for each factor considered in this study was estimated using the methods of AHP and pairwise comparison matrix. The definitions and explanations of AHP and the pairwise comparison matrix are tabulated in Table 3 and Table 4 respectively. AHP is a structured technique for decision-making based on a hierarchical framework constructed through mathematical pairwise comparisons in which each factor will be assigned a weight representing the relative importance of each factor in the overlay suitability analysis. The scale of relative importance contained absolute numbers from 1, which represented the equal importance of the two factors, to 9, which represented extreme importance for the first factor compared to the other.

Table 3: Scale of pairwise comparisons

Intensity of importance	Definition	Explanation
1	Equal Importance	Two activities are equally important to the objective
3	Moderate importance	One activity is moderately more important
5	Strong importance	One activity is strongly more important
7	Very strong importance	One activity is favoured very strongly over the other; demonstrated to be much more important
9	Extremely importance	One activity is demonstrated to be important at the highest level
2,4,6,8	Intermediate values	When a compromise between the above odd numbers is needed

Source: Modified from Saaty (1980)

Table 4: Weight and pairwise matrix of suitability criteria

Matrix	LULC	Road	Substation	River	Dumpsite	Slope	Weight
LULC	1	3	3	5	5	5	0.38
Road	1/3	1	3	3	5	5	0.25
Substation	1/3	1/3	1	3	3	3	0.16
River	1/5	1/3	1/3	1	3	2	0.11
Dumpsite	1/5	1/5	1/3	1/3	1	1	0.06
Slope	1/5	1/5	1/3	1/2	1	1	0.04
Total							1

Integrated Suitable Analysis

Analysis of individual criteria alone does not provide a comprehensive evaluation and can lead to conflicting results, as illustrated in Figure 3. The weighted overlay method can be used to integrate these criteria and generate a more comprehensive suitability map.

The final suitability map of a WtE facility site is based on the characteristics of the site that reduce construction cost, transportation cost, and energy losses in the transmission lines while minimizing environmental impacts in the study area. Lawal *et al.* (2011) state that a consistency ratio of less than or equal to 0.1 signifies an acceptable reciprocal matrix. It was established from this study that the consistency ratio of 0.07 was acceptable for processing overlay analysis and standardizing each data set to a common scale of 1, 2, 3, 4, 5 (1 = unsuitable, 2 = less suitable, 3 = moderately suitable, 4 = suitable, and 5 = highly suitable).

Based on this process, a five-scale scoring system was selected to categorize the data in each layer as shown in Table 5. This categorizes the data from highly suitable to unsuitable, with 9 as the highest-ranked score and 1 as the lowest.

Table 5: Data Suitability Classes

Rank	Suitability class
9	Highly suitable
7	Suitable
5	Moderately suitable
2	Least suitable
1	Unsuitable

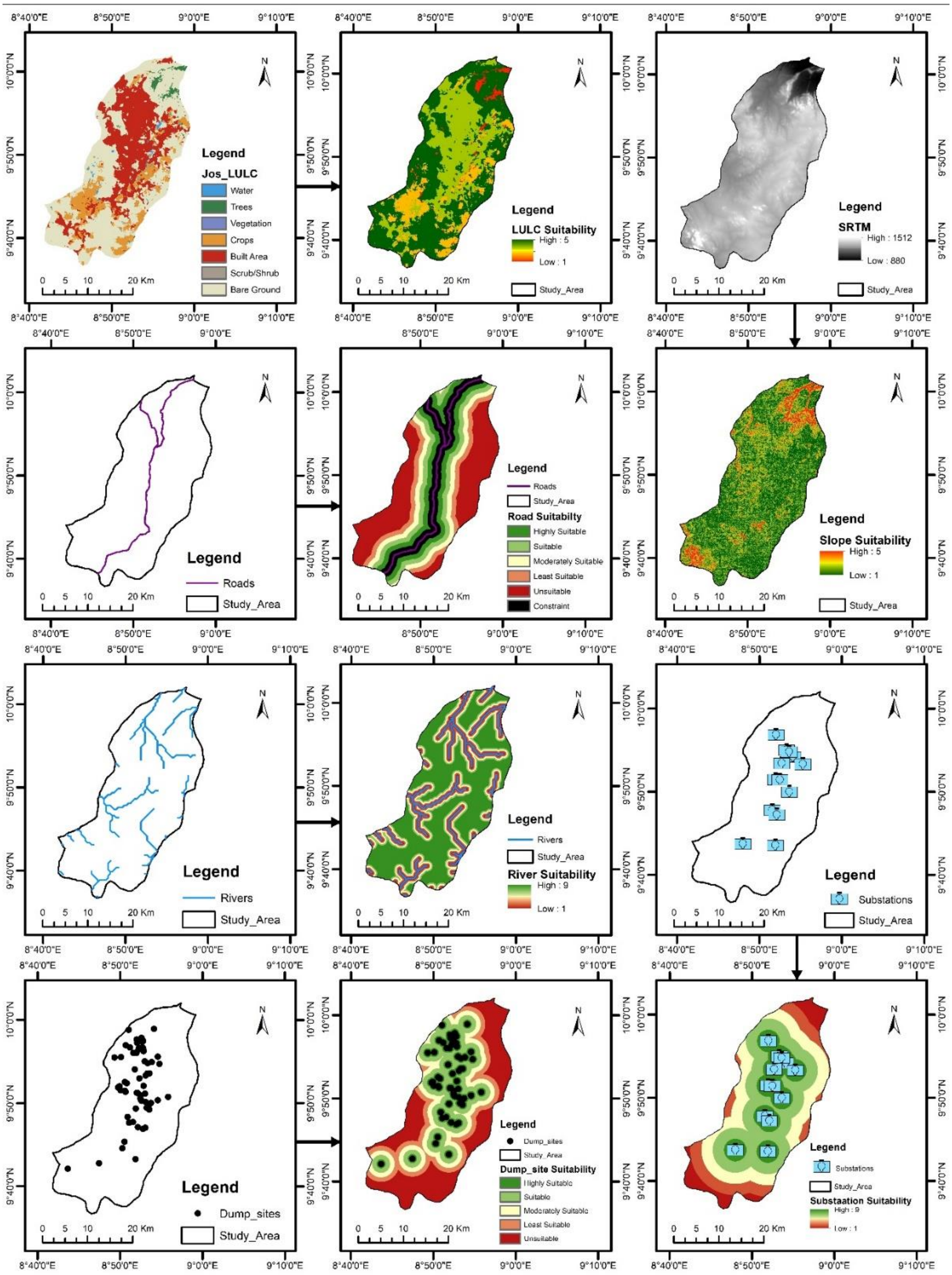

Figure 3: Procedures and results of Reclassified layers

A multi-criteria analysis was carried out to identify a suitable site for WtE facility. The WtE facility site selection was governed by a compilation of standards stipulated by the Nigerian Environmental Standard and Regulation Enforcement Agency (NESREA), Mipun (2015), Adegbite *et al.,* (2020), Ghoutum *et al.,* (2020), Abushammala *et al* (2022) for each land use pattern. The weights derived from the AHP were attributed to their respective raster layers and with the use of the weightage overlay tool in ArcGIS.

RESULT

Estimated waste generated: Estimating the amount of waste generated is essential for effective waste management planning and decision-making. Figure 2 presents the estimated amount of waste generated in the study area.

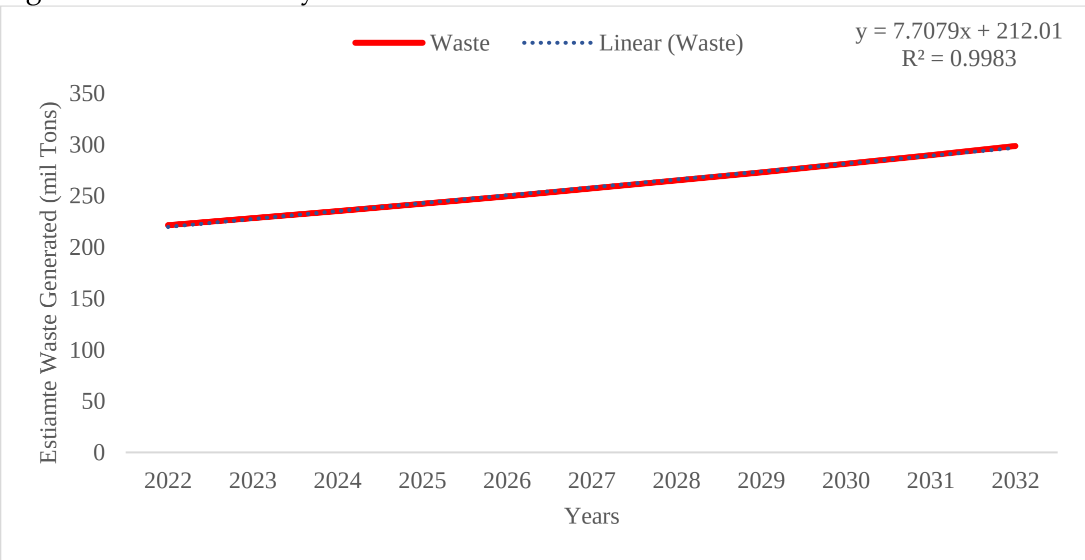

Figure 4.1: Estimated amount of Waste Generation in the Study Area

The findings unveiled that the bustling Jos metropolis produces approximately 221 tons of waste daily. This staggering amount highlights the urgent need for effective waste management strategies in the area. Furthermore, the data indicate a concerning projection of 299 tons per day by the year 2032, signifying a significant 35.29% increase within a decade.

Waste to energy facility suitability in Jos Metropolis: Results from the weighted overlay map indicate that areas that are most suitable for a Waste-to-Energy facility cover 2.8% (23.3 Km²) of the total land area and are located at an appropriate distance from roads, substations, dump sites, and water bodies. 20.1% (168.8 Km²) of the area is suitable, 41.7% (350.5 Km²) is moderately suitable, 17.9% (150.3 Km²) less suitable, and 1.2% (137.7 Km²) is deemed unsuitable (Table 5).

Table 5: WtE Suitability and Area Coverage

WtE Suitability	Area (Km²)	Area (%)
Highly Suitable	23.3	2.8
Suitable	168.8	20.1
Moderately Suitable	350.5	41.7
Less Suitable	150.3	17.9
Unsuitable	10.1	1.2
Restricted Areas	137.7	16.4
Total	**841**	**100**

The findings of the study reveal that the regions of Jarawa and Vwang are unsuitable for the establishment of a Waste-to-Energy (WtE) facility primarily due to inadequate road infrastructure. Furthermore, the presence of highlands in the surrounding areas would result in additional expenses for road construction and adversely affect the fuel efficiency of waste transportation trucks. On the other hand, potential sites exhibiting suitable to moderately suitable conditions are scattered across the central and southern parts of the study area, benefiting from their proximity to power substations and access to well-developed road networks.

Among the identified potential sites, Gyel 'A', Gyel 'B', Kuru 'A', and Kuru 'B' hold the highest promise for establishing a WtE facility. However, after careful evaluation, Kuru 'A' has emerged as the optimal choice as illustrated in Figure 4. This decision is based on several factors , including proximity to the power substation and road network, convenient access to dump sites, and reasonable distance from water bodies (Figure 3). This location not only offers cost-effectiveness but also minimizes potential risks to the local population and economic activities.

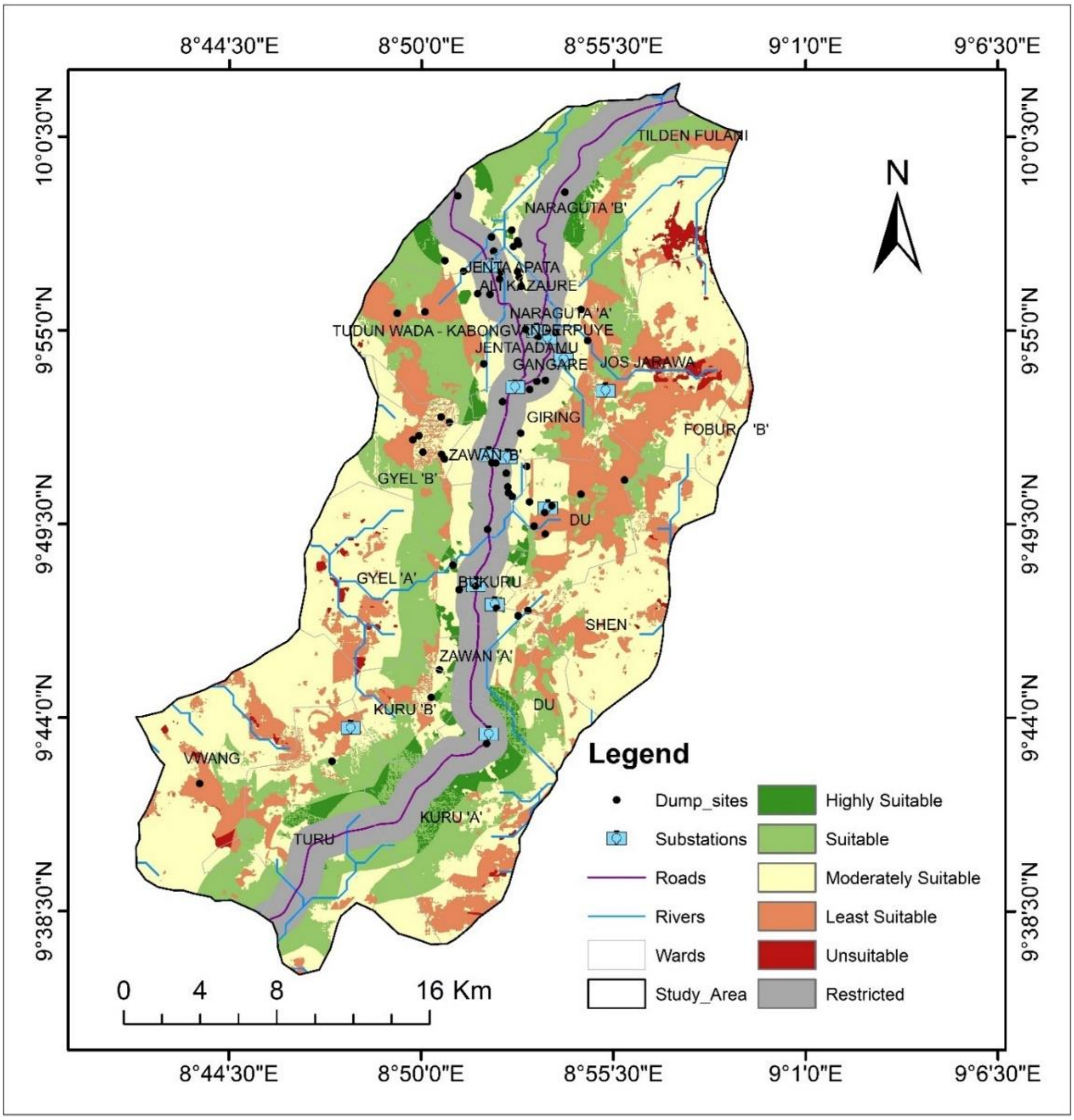

Figure 4: Suitable Site for Waste to Energy Facility

CONCLUSION

The establishment of a Waste-to-Energy (WtE) facility serves a crucial purpose in safeguarding the environment by mitigating the adverse effects of waste on resources and community health, while concurrently providing a sustainable source of energy. In a recent study, it has been determined that Jarawa and Vwang are not suitable locations for a WtE facility due to inadequate road infrastructure. However, potential sites within the central and southern regions of the study area, namely Gyel 'A', Gyel 'B', Kuru 'A', and Kuru 'B', have been identified as viable alternatives.

Among these options, Kuru 'A' emerges as the optimal choice owing to its advantageous proximity to power substations, well-established road networks, existing dump sites, and minimal risks posed to people and economic activities. The selection of Kuru 'A' ensures cost-effectiveness and efficient waste management practices, thereby offering a comprehensive solution.

The study employs the Weighted Overlay Analysis (WOA) approach, which leverages the capabilities of Geographic Information System (GIS) technology to handle large volumes of data from diverse sources. This approach is highly effective in minimizing the potential negative impacts of WtE facilities. Utilizing the WOA approach, the study provides a robust framework to guide future decision-making processes concerning selecting suitable WtE facility sites within the Jos metropolis.

The findings of this study hold significant value, offering valuable insights and recommendations for stakeholders involved in the planning and implementation of WtE facilities. By incorporating these results into future decision-making processes, environmental and community welfare concerns can be effectively addressed while harnessing the benefits of sustainable energy generation through WtE technologies.

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