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Proximate analysis of waste-to-energy potential of municipal solid waste for sustainable renewable energy generation

I.M. Lawal [a,*], A. Ndagi [a], A. Mohammed [a], Saleh Y.Y. [d], A. Shuaibu [b], I. Hassan [a], S. Abubakar [a], U.B. Soja [c], A.H. Jagaba [a]

[a] Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi, 740272, Nigeria
[b] Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria, 810107, Nigeria
[c] Department of Civil Engineering, Federal University Dutsin-Ma, Katsina, 821101, Nigeria
[d] Nigerian Upstream Petroleum Regulatory Commission, Warri Delta, 331221, Nigeria

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ABSTRACT

Over-dependence on virgin resources has been a major topic of social and political debates as the world's population and urbanization continue to rise. The high rate of rural–urban migration and changes in standard of living habits give rise to rapid economic activities that have an enormous impact on the gradual increase in waste generation and continued demand for electricity in urban centres. The solutions to these concerns can be achieved through efficient waste management options by waste resource utilization for energy and nutrient recovery and reduced solid waste pollution footprint. This research examined the viability of present and projected municipal solid waste streams to generate green energy through field surveys by physical characterization of the waste composition, projected waste quantity based on available population and waste data for the period 2000 – 2014, modelled methane gas generated by IPCC method, and the energy value was determined respectively. The findings indicated a high organic content of 54.1% of MSW and a per capita waste generation rate of 0.49–0.57 kg/capita/day. The waste was projected to increase from 353717.41 to 2,223497 tonnes between 2014 and 2035 at a population growth rate of 9.15%. This accounted for methane gas generated estimated to be 9.85Gg/year with an energy value of 15 MW/day in 2014 and projected to increase to 33.4 MW/day by 2035. The energy value estimated represented an increase from 6.14% to 212.74% of the allocated power supply from the national grid within the projected period. However, it is worth noting that, there are some limitations associated with the research due in part to inadequate field data which was supplemented by default model values as recommended by IPCC, although within an acceptable uncertainty band of result sensitivity. Therefore, the WTE management option can serve as a pathway for green energy integration for sustainable development.

1. Introduction

There are enormous problems associated with solid waste management practices in developing economies, such as the inadequate commitment of financial resources and infrastructure that leads to poor quality of waste management service [1–3], increased population and urbanization only increase the volume of waste generated and demand for collection services in the cities [4]. Reliable data for proper waste management is lacking in many developing countries [5] and where such data are available; they are often inconsistent which generally affects a comprehensive and critical evaluation of the available waste management strategies for effective and efficient waste management programmes [6–9]. In Nigeria, data on municipal solid waste generation and composition are generally inadequate and available for few metropolitan cities, nationwide statistics are lacking and invariably complicate popular waste management options. Similarly, high population growth rate, rural–urban migration, increased socio-economic activities in urban areas, and inadequate training in modern solid waste management in developing countries in the collection,

* Corresponding author.
E-mail address: mlibrahim@atbu.edu.ng (I.M. Lawal).

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processing, disposal and reuse efficiently is limited compared to the advanced economies [10,11].

It has been shown that the majority of developing and developed countries' municipal solid waste is organic or food waste [12,13]. In Europe and USA, it was found that 36.4 and 89 million tonnes of organic waste are respectively generated annually [14,15]. However, in third-world world countries, for example, China, the composition forms 50% of the total municipal solid waste, although highly variable depending on the source, standard of living, income level, local regulation, moisture content, etc. and was projected to increase in the future [16–18], and generally serve as a feedstock for renewable energy production through bioconversion owing to its biodegradability [19,20], and it is posited to contribute approximately 20% of the world energy consumption in 2020 [21,22]. Improper management of municipal solid waste often causes a lot of negative environmental issues ranging from greenhouse gas emissions, diseases, and odour problems, to increased pollution levels and loss of resources [23].

Fossil fuels have been the primary source of energy infrastructure for the majority of developing nations, but they are also one of the major causes of anthropogenic carbon dioxide (CO2) emissions, which significantly contributes to global warming and climate change [24,25]. Long-term initiatives for sustainable and green (renewable) energy sources that seem to be effective and efficient solutions in the future can help to solve environmental concerns [26,27]. Anaerobic digestions, which produce energy-dense biogas that is used for vehicle fuel, electricity, heat energy, and the residue, commonly referred to as digestate, used for fertiliser production, are the method used to produce the biogas that was once thought of as clean and green energy from a variety of municipal solid and liquid waste [28–30]. This strategy has been proven to be economically feasible to optimize municipal solid waste management options [31].

The availability of clean and green energy in sufficient and sustainable amounts has gained recent world research interest and becomes the main driver for economic and social development [31]. The procedure entails using waste-to-energy (WTE) plants to turn industrial, agricultural, and municipal solid wastes (MSW) into a source of energy while reducing the amount of waste produced and addressing the twin issues of land use and landfill pollution as well as the well-known environmental dangers of fossil fuels known as greenhouse gas emissions (GHG) [32,33].

More than 50% of the world's population was anticipated to reside in urban areas in 2008, and by 2030, that number is expected to rise by almost 5 billion. These cities were mostly located in underdeveloped nations [34]. The volume of municipal solid garbage has been steadily increasing over the past three decades as a result of the growing population and higher living standards [35] and may overstretch the waste management infrastructure and becomes a burgeoning problem for local, state and federal authorities in low to medium income nations for effective and sustainable waste management [36]. In most countries, waste policies that bother around reduction, reuse and diversion from landfills are strongly encouraged, although more than 50% of the member state still sends an excess of 75% of their waste to landfills [37]. The practice is also common in the Federal Capital City, Abuja in Nigeria.

One of the cities with the fastest population growth, Abuja Municipal Area generates roughly 353,717.41 tonnes of MSW annually as of 2014, with degradable organic waste making up about 65% of its composition (AEPB). The city population is projected to increase at a rate of 9.75% which suggests a future generation of a large volume of MSW which if not adequately managed, could impair the environmental living standards and quality of residents. The underlying issue calls for the development of a waste management strategy through a comprehensive waste audit and adopting the best management options.

Nigeria's power production has fluctuated between 4000 MW and a little bit above that to support a population of about 200 million people [38] and the power allocated to the city is around 11.5% of the generated power as of 2015 [39]. This led the public to seek alternative power supplies such as petrol and diesel generators which consumed a staggering $ 250 million annually in the cost of generating set and its accessories and was projected to increase rapidly in the future [40]. This phenomenon has been a critical issue in developing economies, especially in Africa where a larger proportion of the population does not have access to adequate energy supplies [41]. This study is important due in part to the rising environmental pollution concerns [42], as some of the waste materials found in MSW are hazardous by-products of industrial processes that require careful and efficient disposal [43].

Furthermore, it is proposed that comprehension of potentials for future energy recovery is crucial and offers an understanding of how WTE technologies fit into waste management strategies [44], and that will further prevent the negative effects of MSW disposal in landfills such as fire outbreaks, unpleasant odours that may affect environmental air quality, groundwater recontamination etc. [27,45]. There is growing research interest across disciplines on waste reuse options to create value for money whose impact has been reported recently, for example [46] posited that an effective waste treatment plan is positively correlated to renewable energy generation by 5.74–12%, additionally, renewable energy and transport services can significantly have an impact on economic growth and international tourism development [47], and finally, waste reuse options can enhance efficiency and exclude the additional expenses for landfill waste disposal [48,49].

Several research on municipal solid waste management has been conducted in Abuja Municipal Area Council that bothers around waste audit and management options [50], trends, status and attitudes towards solid waste management [51–53]. However, none of the research examined the viability of the current and projected waste stream as a feedstock for an alternative source of energy generation which is the focus of this research with the following objectives: to examine the reliability of the available waste generation data in Abuja, characterize the waste from the dumpsites and estimate the proportion of the biodegradable component of the MSW, to project the MSW generation and amount of landfill, carbon dioxide and methane gas to be generated and finally to estimate the potential amount of energy to be generated from the waste streams.

This proximate assessment is considered a novel approach by understanding the structural changes of waste streams and integrating variables such as waste collection rates, population dynamics and growth rates and prevailing climate to drive the course of green energy production in evaluating the viability of sustainably integrating solid waste into the national green energy mix and provide a pathway for field-based application, especially in regions with inadequate long term empirical database for accurate and consistent waste to energy studies, which has not been explored. The assessment can quickly support favourable policies that could prevent the widespread implementation of waste-to-energy technologies that could offer an opportunity and solutions for energy recovery and reduction of landfill waste footprint, as well as improve net zero emission targets for sustainable development.

2. Materials and method

2.1. Study area

Nigeria's Federal Capital Territory (FCT), Abuja, with a land size of 7,753.9 km^2, became the nation's capital in 1991. The Gwagwa plains in the northeastern corner of the FCT are home to the capital city, Abuja, which covers an area of around 250 km^2 [54]. It lies between the geographic coordinate of latitude (7° 25′ N–9° 20′ N) and longitude (5° 45′ E–7° 39′ E) at an elevation of 476 m (1561 ft.) [50]. Abuja has a population of about 1,700,101 as of 2014 (NBS) with an annual waste generation estimated to be 353,717.41 Tonnes/year (AEPB). Six area councils made up the pre-planned city: AMAC, Bwari, Gwagwalada, Kuje, Kwali, and Abaji. Districts were a further division of the Area councils [55].

There are four waste dumpsites in Abuja: Mpape, Gosa, Ajata, and Kubwa. Currently, only two of them are run by the AEPB. The 16-hectare Mpape dumpsite, which had a garbage depth of 15 to 30 m, was first operational in 1989 and shut down in 2005. The Kubwa dumpsite was forced to close owing to odour and random fire outbreaks after being opened in 2004 and 1999, respectively. Currently, only Gosa and Ajata landfills are operational [55]. In this study waste stream from the Gosa dumpsite was utilized for characterization. Fig. 1 shows the location of Abuja and Gosa dumpsite, respectively.

The study utilized data from primary and secondary sources that involves waste characterization from the MSW dumpsites through a field survey (Fig. 2a-f) and sampling using a weighing balance, hand gloves, plastic sheet (sorting platform), shovel, face mask etc. Estimated annual waste quantities and population data from the Abuja Environmental Protection Board (AEPB) and National Bureau of Statistics (NBS) for the year 2000 – 2014 respectively (Fig. 3) and relevant literature regarding the waste characterization and landfill gas utilization was consulted.

2.2. Municipal solid waste characterization

A field survey was carried out for the characterization and analysis of the waste. This was carried out by hand sorting at the disposal facility to characterize the waste according to the guidelines provided by United Nations Environmental Programme on MSW characterization. According to [56], This technique generates the most precise waste characterization information and is particularly appropriate for garbage that is often made up of multiple small particles of various materials. Although a full vehicle load of waste was typically recognised for sampling, only a part of the load was hauled out for sorting. This technique was necessary for the accurate categorization of household or business garbage.

At the site, three samples of 15 kg weight each were collected randomly in waste polythene bags to make up a total of 45 kg. The waste was sorted, and each portion was weighed and analysed. An average of three samples was taken to make one, and the process was repeated for 2 weeks for consistency. Seven waste components were considered for classification, these were food, paper, iron & tins, glass & bottles, rubber & polythene, plastics & ceramics, and others. Other solid trash in this category includes items like fabrics, wood shavings, hospital waste, mechanical garbage, computer parts, etc. that are not readily recognisable or do not fit into the other six categories.

This task required the use of protective equipment for safety. Subsequently, all wastes were dumped, and the equipment used was cleaned. The average of this result was taken and used to represent the percentage of compositions of municipal waste generated in the Capital city, Abuja. The data was analysed, and a proximate and ultimate analysis was carried out on the collated result.

The percentage composition of the waste fraction and per capita generation rate was determined based on Eqs. (1) and (2) respectively as given below.

$$\%Compositionofwaste = \frac{WeightofSeparatedwaste}{Totalwastewastesamplecollected} \times 100 \quad (1)$$

$$PerCapitawastegenerated(kgper\frac{cap}{day}) = \frac{AnnualWeightofwastegenerated}{Annualpopulation \times 365} \quad (2)$$

2.3. Estimation of methane yield

Methane yield was estimated based on the recommended guideline of the Intergovernmental Panel on Climate Change [57,58], predicated on the premise that the gas yield was released the same year the garbage was disposed of, which was a straightforward mass balance calculation that determined the amount of methane gas emitted from the solid waste disposal sites (SWDS).

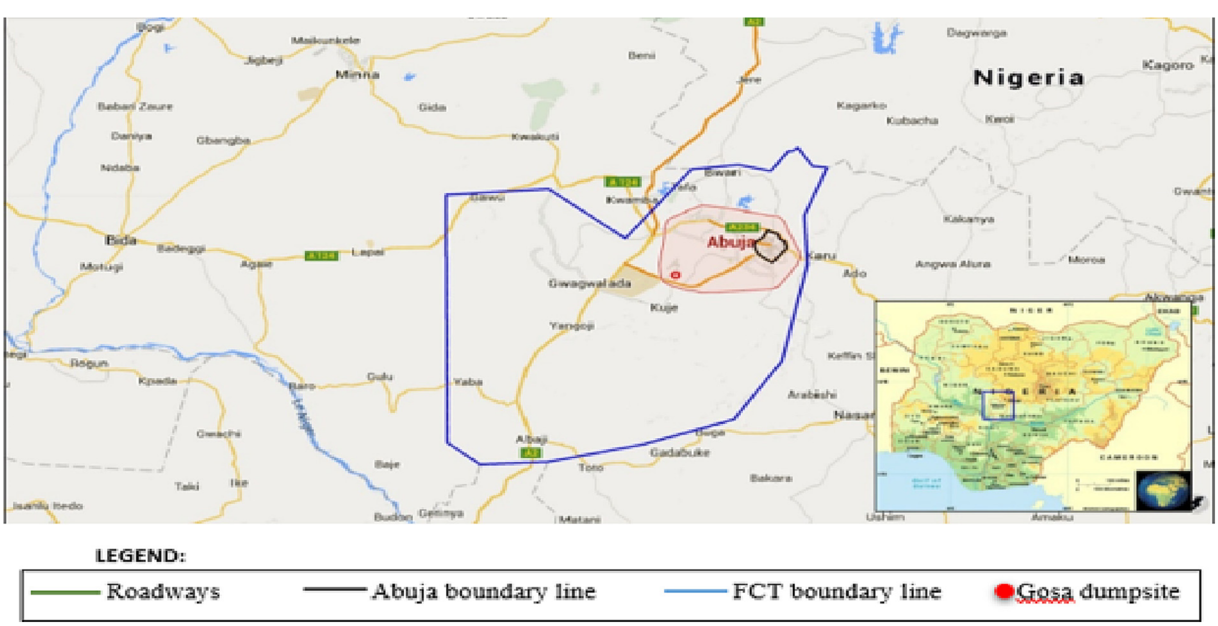

Fig. 1. Map of FCT Showing Abuja, other Area Councils and Gosa Dumpsite.

Fig. 2. (a-f) Field Survey of operational activities at Gosa dumpsite Abuja.

$$CH_4Emi.\left(\frac{Gg}{yr}\right) = \left[MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F\left(\frac{16}{12} - R\right) \times (1 - OX)\right] \quad (3)$$

Where:

MSW_T = Total Municipal Solid Waste (MSW) generated (Gg/yr.) (Product of Population and annual waste generation).

MSW_F = Fraction of MSW disposed at the dump site; (assumed as 74% of MSW_T generated was collected and disposed at the dumpsite.

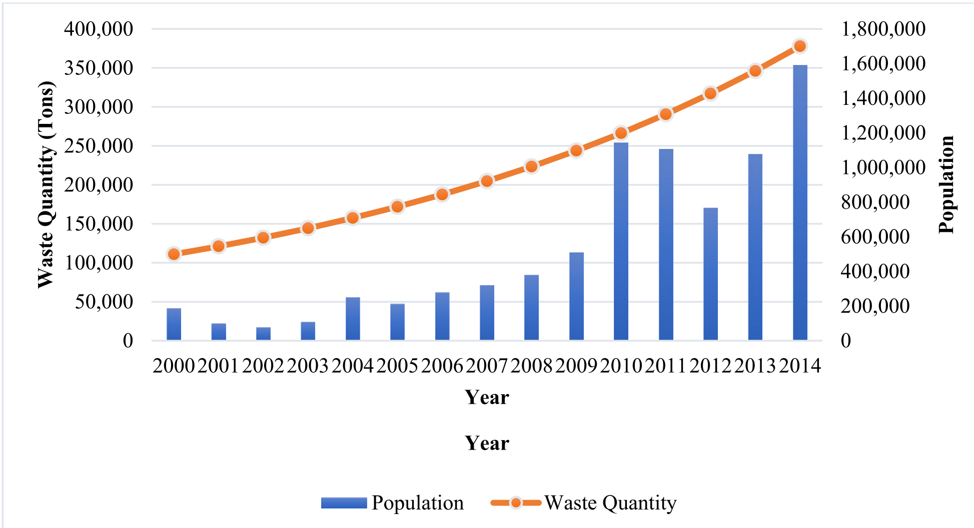

Fig. 3. Annual waste generation and population relationship with time in Abuja metropolis.

MCF = Methane correction factor (Fraction); ranged between 0.4 for shallow unmanaged sites to 1.0 for managed sites above 5 m deep, a default value of 0.6 was adopted in this study for unspecified SWDS.

DOC = Degradable organic carbon (fraction), estimated using the equation below

$$\%DOC = 0.4A + 0.17B + 0.15C + 0.30D \quad (4)$$

Where:

A = % MSW that is paper and Textiles.
B = % MSW that is garden waste, park waste or other non-food organic waste.
C = % MSW that is food waste.
D = % MSW that is wood or straw, 20% of the MSW composition termed others were used.
DOC_F = Fraction of DOC that was converted to gas and was estimated from the equation below

$$DOC_F = 0.014T + 0.28 \quad (5)$$

Where:

T is the temperature of the site. The site temperature at the time of the field survey was 28C.

F = Fraction of methane in the landfill gas (IPCC default value of 0.5 was adopted).

R = Recovered CH_4 (Gg/yr.), 0.

OX = oxidation factor (Default value of zero was adopted).

2.4. Estimation of potential methane generation capacity of the MSW

The methane gas of the MSW generated annually was converted to its generation potential, L_o (m^3/Gg MSW) from the equation below,

$$\text{Lo}\left(\frac{\text{m}^3}{\text{Gg}}\text{of MSW}\right) = \frac{(CH_4(kg))}{0.717(\text{kg}/\text{m}^3} \times \frac{1}{MSW_T(\frac{Gg}{yr})} \quad (6)$$

Where:

L_o = Methane generation potential.
Density of Methane = 0.717.
CH_4 = weight of Methane in kg.
MSW_T = Total Municipal Solid Waste generated (Gg/yr.).

The waste-to-energy potential of the methane gas was estimated using the recommendation made by [59], that a normalized cubic meter of methane gas was equivalent to 10 kWh. The projection of landfill gas was based on several factors like average population growth rate, per capita waste generation rate [60,61] and variables in the IPCC, 1996 model equations incorporated in the United States Landfill Gas Emission Model (LandGEM) V.3.02 software and projected for the year 2015 – 2035.

3. Results and discussions

The secondary data used in this study, are annual waste generation quantity and population of the Abuja municipal area (Fig. 3), the data indicates that there is a consistent increase in both quantities from 2000 to 2014 and the average population growth rate is 8.55% and 9.75% from 1991 to 2006 and 2006–2014, respectively. As a result, an average population growth rate of 9.15% was recommended in the future projection by the National Bureau of Statistics (NBS) for the year 2020–2035. The per capita waste generation rate was estimated to be 0.42–0.57 kg/capita/day for the period 2000–2014. The estimated per capita waste generation of 0.57 kg/capita/day was adopted to project future waste generation quantity.

3.1. Physical characterization of municipal solid waste

The various compositions of the samples of the MSW collected over a period of two weeks were subjected to a homogeneity test using one sample student T-Test. A t-value of 2.817 was computed against a critical value of 2.145 which indicated that the null hypothesis can be accepted and that the municipal waste compositions are homogeneous at a 95% level of confidence.

Based on the data from the field survey, the average municipal waste composition of the Abuja municipal area council (Table 1) characterized are as follows: Food/Putrescible (54.1%), Paper (10.5%), Glass and Bottles (4.8%), Tin and Metals (3.8%), Plastic and Ceramics (8.7%), Rubber and Polythene (9.9%) and others (8.3%). It was observed that the dominant waste category is the biodegradable waste fraction of the MSW. The high percentage of paper, polythene and plastic waste is due to the high-rate economic activities and use of Cans, beverages, and polythene bags in commercial areas of the city.

Table 1
Composition of Municipal Solid Waste in Abuja.

Waste Type	Mass (kg)	Percentage (%)
Food/putrescible	24.3	54.1
Paper	4.7	10.5
Glass & Bottle	2.2	4.8
Tin & metals	1.7	3.8
Plastic & ceramics	3.9	8.7
Rubber & polythene	4.5	9.9
Others	3.7	8.2
TOTAL	**45**	**100**

Source: Field Survey and Sampling.

The Food/Putrescible which was termed the organic composition of the waste stream is completely bio-degradable and the focus of this study. The result of the waste stream composition from the Gosa dumpsite based on composition (Fig. 4) and per capita generation rate is supported by the study [50,51].

3.2. Projection of municipal solid waste stream

Based on the city's anticipated population for the years 2020 to 2035 and the adopted per capita trash generation rate, the predicted municipal solid waste stream in the study region was calculated (Fig. 5) at an average population growth rate of 9.15%. In the year 2035, the population was projected to be 10,689.890 people and an estimated waste generation quantity of 2,223,497 tonnes/yr. This revealed that the MSW has the potential of producing a substantial amount of energy from the waste stream owing to having the highest composition being biodegradable.

Table 2
Parameters used in Estimating Methane generation potential.

PARAMETER	VALUE
Total Municipal Solid Waste Generated, MSW_T	353.72 Gg
Fraction of MSW disposed at the dumpsite, MSW_F	261.75 Gg
Methane Correction Factor, MCF	0.6
Degradable Organic Carbon, DOC	0.14
Fraction of DOC converted to gas, DOC_F	0.672
Fraction of CH_4 in the Landfill gas, F	0.5
Recovered CH_4 , R	0
Oxidation factor, O_x	0
% MSW that is Paper & Textile, A	10.50%
% MSW that is garden waste/other non-food organic waste, B	6.20%
% MSW that is food waste, C	54.10%
% MSW that is wood or straw, D	2%
Average Temperature at the Landfill site, T	28 °C
Methane density	0.717 kg/m^3

3.3. Methane gas potential and energy value from MSW

The methane gas potential and energy value from the municipal solid waste were estimated using the available annual waste data

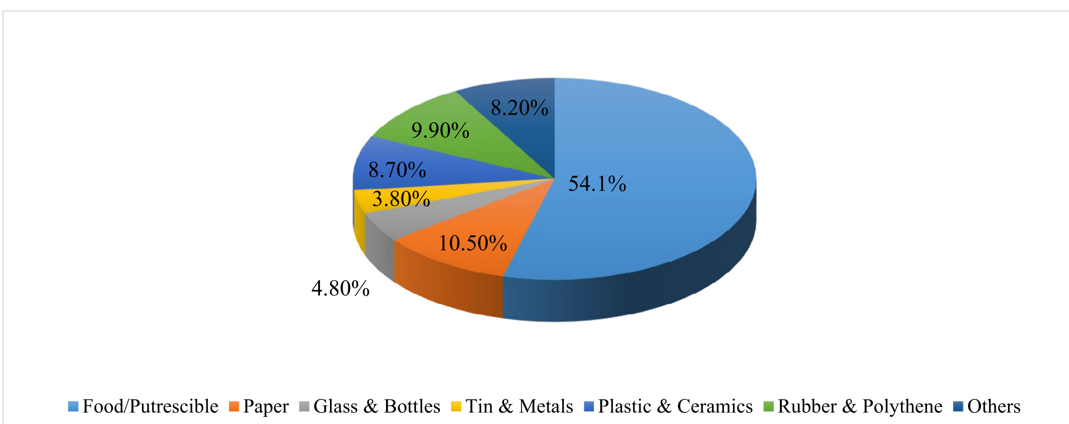

Fig. 4. Composition of Municipal Solid Waste in Gosa Dumpsite Abuja.

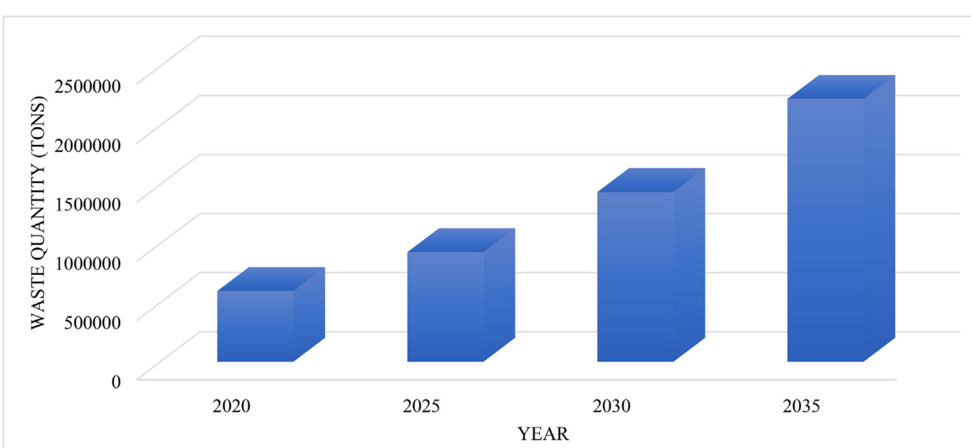

Fig. 5. Solid Waste generation projection for Abuja Municipal Area.

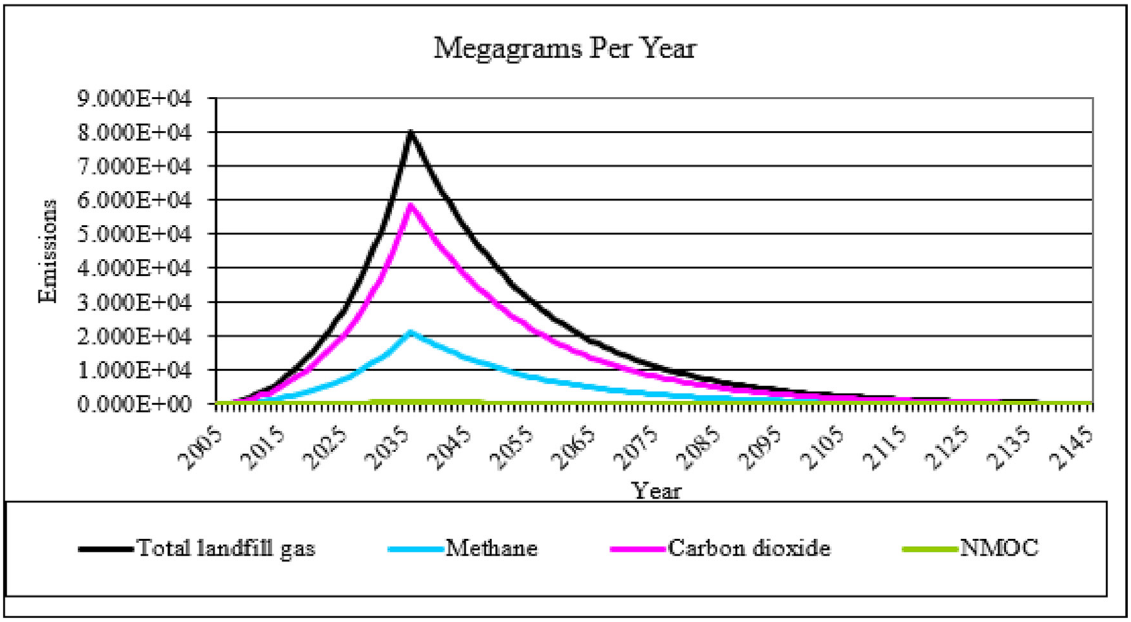

Fig. 6. MSW gas generation projection plot in Mg for the closure year 2035.

Table 3
Estimated Methane generation and energy potentials of MSW.

PARAMETEER	VALUE
Methane generation	9.85 Gg/yr.
Generated Volume of methane	13,734,754 m^3
Potential methane generation capacity, L_O	38,830 m^3/Gg
Energy Value of methane	137,347.54 MWhr
Electrical Power	15.7 MW/day

in 2014 and the projection made in 2035 from LandGEM V.3.02 based on the landfill opening and closure years of 2005 and 2035 respectively, and the input parameters estimated guided by Eqs. (3)–(6) shown in Table 2.

The estimated methane gas emission was based on the theoretical gas yield because of its versatility and wider application in regions where detailed empirical data are inadequate, although it does not provide accurate estimates due to its assumption that all potential methane was released in the year MSW was disposed of, however, the results are dependable. The parameters used for the estimation are given in Table 2, it was observed from the results that landfill gas generation increased significantly until the closure year of the dumpsite where an exponential decrease up to the end of the century was observed (Fig. 6). The results of methane gas volume and estimated energy value are given in Table 3 below for the year 2014. The estimated energy value from the MSW of 15.7 MW/day represents 6.4% of the total daily allocated energy to Abuja municipal area as of 2014.

The results of the gas generation projection for the closure year 2035 indicate a methane generation volume of 1.955×10^4 Mg, with an equivalent energy potential of 293,000 MWhr (33.4 MW/day) i.e., 212.74% increase in energy value in a span of 20 years.

4. Conclusion and recommendations

The study's findings and limitations, such as the lack of current waste generation statistics and estimations of the default IPCC model's methane generation potentials, guided the conclusions that were reached. According to the study, the municipal solid waste stream in the Abuja Municipal Area Council is growing over time. It went from 41,402 tonnes to 353,717.41 tonnes between the years 2000 and 2014, respectively, and it was predicted that it would reach 2,223,497 tonnes by the year 2035. Rapid urbanisation, a rise in the standard of living, and population growth were all associated with this increase in waste streams. A sustainable management approach offers the potential to recover energy and nutrients from the waste stream's substantial biodegradable (54.1%) and recyclable (29.1%) content.

The municipal solid waste composition has the potential of generating 15.7 MW/day of electrical energy based on 2014 data and that represents 6.41% of allocated power supply from the national grid to Abuja municipal area and the amount was projected to increase to 33.4 MW/day (212.74%) by the year 2035.

The waste composition analysis helps in the planning and management of future trends. Source separation through sensitization and public awareness will serve as an important process to achieve an effective and efficient path towards a sustainable solid waste management programme. Furthermore, it will help in preserving valuable resources, reduce negative environmental impact and huge land take from the additional landfill sites to cater for the exponential growth of waste streams.

However, further research will be done in this area because the procedure could need a cost-benefit analysis. The cost-benefit analysis will also assist in assessing the economic sustainability of this resource recovery option to educate responsible authorities and policymakers of the costs associated with adoption in MSW management practice. Additionally, it is important to note that the study's conclusion can be strengthened by using current, accurate physical and chemical waste characterisation data instead of the recommended default model assumed values, which could affect the output variables' sensitivity, particularly the landfill gas volumes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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