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Characterization and Estimation of Methane Emissions in Municipal Solid Wastes for Power Generation: A Case Study

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Abstract: Sustainable management of environmental waste is an important facet of our modern society. Generation of Municipal Solid Waste (MSW) gives rise to some serious socioeconomic and environmental burdens. Considerable amount of anthropogenic Greenhouse Gas (GHG) emissions from open waste dumping sites is a major global challenge. Increasing human population and continue expansion of urban settlements, especially in developing countries are responsible for sharp increase in MSW generation. However, conventional MSW management approaches bring a lot of environmental constraints such as greenhouse gas emissions, soil pollution and groundwater contamination. Researches focusing on waste management for energy generation constitutes an integral part sustainable development. In this study, methane emissions from major landfill sites in Nigeria administrative state capitals and major cities are estimated. Intergovernmental Panel on Climate Change (IPCC) default approach is used to calculate the mass of methane emissions and the equivalent power generation potential in each of the cities is also evaluated. A total of 335.2 MW electrical power is obtained for the cities in all the geopolitical zones in the country.

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INTRODUCTION

Generation of municipal solid wastes in our modern societies are inescapable undertakings. Therefore, the concept of waste generation is an integral and consequential part of our modern global society. The term 'wastes' could be used to describe discarded materials such as rubbles, garbage, refuses and unwanted by-products. Wastes are categorically inseparable from human existence but if they are not properly handled, they have tremendous potential to impact our healthy environment in negative ways. As human population continuously increase, rural communities developed into towns where some in progression of time developed into cities with robust economic evolution with corresponding high volume of waste generation. In many developing countries, especially in Sub-Sahara Africa (SSA), waste materials are discarded indiscriminately into unapproved landfill sites and waterways. As a result of increasing global population, economic growth, unsustainable lifestyle and escalating urbanization, global solid waste generation was projected to have increased in a century from 110 million tonnes in 1900-1.1 billion tonnes in 2000 (Hoornweg *et al*., 2013). Globally, MSW is presently estimated to approximately 1.3 billion tonnes annually and expected to rise to as much as 2.2 billion tonnes per year by 2025 (Scarlat *et al*., 2015). Certainly, the global per capita waste generation will increase in the next few decades considering the dynamics of the current socioeconomic set-ups. On this account, it was anticipated that the present average value of 1.2 kg per person per day will increase to 1.42 kg per person per day until 2025.

In the past centuries, waste disposal is quite not as cumbersome as presently as it is today. The present day industrial revolutions coupled with new urban life with characteristic dynamic economic consumption approach has changed the scenarios of global waste generation. Therefore, the main problems these days are the way to handle, collect, store and the method of disposing wastes without harming the environment. In urban areas with concentrated economic activities, sustainable waste management approach is of great importance in order to provide healthy living conditions. Indiscriminate dumping of waste materials could create serious harmful effects in the form of air and water pollution to the environment. The increasing environmental problems, involving Greenhouse Gas (GHG) emissions into the air and deterioration of water quality, together with the energy crisis and resource scarcity will become more impending in the coming decades, thereby imposing the necessity to embrace actions toward developing a more habitable society (Matsakas *et al*., 2017). The current waste management systems in Nigeria is indeed far from adequate. As a result, Nigeria is in dire need for improvement in waste management techniques in order to reduce the environmental impact from indiscriminate dumping. Utilization of waste for useful energy generation could be one of the prominent concepts for effective waste management in the country. Effective management of MSW requires systematic data collection with regards to waste composition and characterization. Comprehensive waste management statistics are lacking in many developing countries (Buenrostro *et al*., 2001). Therefore, this study presents the characterization and estimation of the biogenic component (methane) of the Municipal Solid Waste (MSW) for power generation in Nigeria.

MATERIALS AND METHODS

Study area: Nigeria is the most populous country in Africa with very rich socioeconomic values. The country is divided into 36 administrative states and six major geopolitical zones. The geopolitical zones are divided into North-West with (7) states, North-East with six (6) states, North-central with (6) states excluding the Federal Capital Territory (Abuja), South-West has (6) states, South-East with (5) states and South-South with (6) states. Abuja is the central administrative capital of the country. Nigeria with an estimated population of close to 200 million occupies a total land area of approximately 923,768 km^2. The map of the country showing the states of the federation and the geopolitical zones is presented in Fig. 1. The country's climate strongly varies from tropical at the centre, arid in the North and predominantly equatorial in the Southern part. Due to economic activities, Nigeria has clustered settlements in the Southern part of the country but predominantly scattered settlements in the Northern part geopolitical zones due to intense agricultural activities.

Generation and characterization of waste materials in Nigeria: The establishment of MSW power project is based on the strategy of waste collection, sorting technique and method of treatment. In rural communities, most of the non-biogenic waste materials generated are recycled for local consumption while the biodegradable contents are either applied as organic fertilizers or used as animal feed. Contrarily, a large proportion of urban biodegradable wastes are discarded in open space landfill sites. A typical MSW consist of both biodegradable and non-biodegradable components. In a waste management approach, characterization of the waste materials is a very important concept. Generation and characterization of waste materials in any part of the world strongly hinge on the sources. Conventional waste types include biodegradable waste, biochemical waste, food waste, e-waste materials, agricultural waste, construction waste, chemical waste, packaging waste, post-consumer waste and others. The compositional characteristics of waste generated in the country is conducted in this study at some selected waste dumping sites in each of the geopolitical zones. The estimated average value of the composition of MSW in percentage is consequently presented in the result section. The selected landfill sites for the compositional analysis are Olusosun (Lagos), Mpape landfill (Abuja), Felele landfill (Lokoja), Court Road landfill (Kano), Njoku Sawmill landfill (Owerri), Ugbowo landfill (Benin), Winti landfill (Bauchi), Umuigwe landfill (Aba) and Nkwelle Ezunaka road landfill (Onitsha).

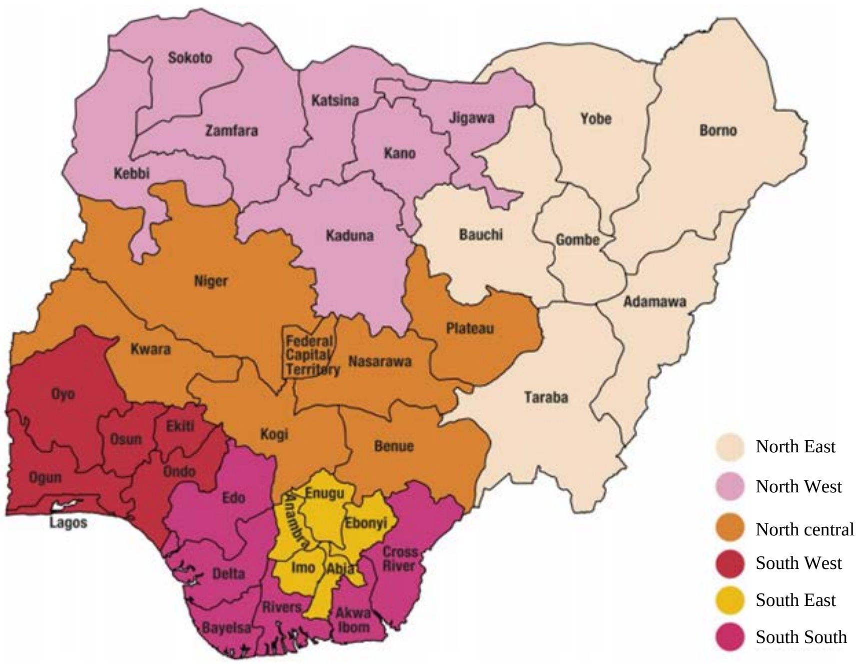

Fig. 1: Map of Nigeria showing the geopolitical zones in the country

Overview of waste-to-energy technologies: Currently, there are some compelling environmental and socioeconomic situations facilitating integration of waste treatment with energy generation. Some materials within a mixed waste like the biodegradable materials can be recovered for energy generation. In this regard, many technological approaches are available for conversion of MSW to energy. The most common technologies of such are anaerobic digestion, incineration, gasification, pyrolysis and sanitary landfill gas power project. Each of these technologies are linked to some peculiar advantages and disadvantages as shown in Table 1. In waste-to-energy concept, the choice of any of these technologies is based on some integrated factors such as socio-economic conditions as well as characteristics and capacity of waste materials generated (Dolgen *et al*., 2005). A waste-to-energy technology can either be accomplished by thermochemical or biochemical means as shown in Fig. 2. The thermochemical approach involves direct combustion of waste materials via incineration, pyrolysis and gasification while the biochemical approach is mainly applied for the production of combustible refuse-derived fuels for power generation (Cheng and Hu, 2010).

Estimation of energy recovery from municipal solid waste: In waste landfilling sites, there is spontaneous anaerobic decomposition of the biogenic (organic) materials in deposited MSW. Gaseous emissions of biogas rich in methane from municipal landfills sites around the world have tremendous negative environmental effects. The methane gas when captured can be used for production of heat energy and electricity in a cogeneration facility (Mostbauer *et al*., 2014). According to Themelis and Ulloa (2007), global landfills generate approximately 75 billion Nm^3 but below 3% of this estimated potential is used for the purpose of energy or heat application. Natural biochemical reactions in waste dumping sites yield to the production of Landfill Gas (LFG) rich in methane. Going by the default method of the Intergovernmental Panel on Climate Change (IPCC, 2006), the estimated quantity of methane production from a waste dumping site can be evaluated using Eq. 1:

$$E_{meth.} = \begin{bmatrix} MSW_T * MSW_F * MCF * \\ DOC * DOC_F * F * \frac{16}{12} \text{-} R \end{bmatrix} (1\text{-}O_x) \quad (1)$$

Where:

$E_{meth.}$ = Mass of Eethane emission in (Gg/year)

MSW_T = Total municipal solid waste generated in (Gg/year)

MSW_F = Fraction of solid waste discarded to landfill sites
MCF = Methane Correction Factor
DOC = Degradable Organic Carbon
DOC_F = Dissimilated Organic Fraction (i.e., fraction converted to LFG)
F = Fraction of methane in landfill gas
R = Recovered methane, the fraction (16:12) molecular weight ratio of methane to carbon
O_x = Oxidation factor

However, Wan and Kadir (2001) stated that 80% of waste materials generated in Nigeria are disposed to landfill. Consequently, the value of MSW_F considered in this study is 0.8. The recovered methane, R and the oxidation factor, O_x are both given the value of zero, since, no methane was recovered from landfill and the biodegradation of waste usually ensue under anaerobic digestion condition, respectively. Thus, Eq. 1 can be rewritten as:

$$E_{meth.} = \begin{bmatrix} MSW_T * MSW_F * MCF * \\ DOC * DOC_F * F * \dfrac{16}{12} \end{bmatrix} \quad (2)$$

In addition, Abushammala *et al*. (2009) evaluated the default value of MCF = 0.6 for unclassified MSW dumping sites. The default values of DOC_F and DOC are 0.77 (Tsai, 2007) and 0.14 (IPCC, 2006), respectively. The fraction of methane in landfill gas vary between 40-65% but F is taken as (50%) 0.50 base on the recommendation of the United States Environmental Protection Agency (US EPA., 2016). Information on the quantity of waste generated in the case study areas as presented in Table 2-4 were obtained from the Renewable Energy Department and Pollution Control of the Federal Ministry of Environment 2010 statistical data. Thus, Eq. 2 gives the mass of methane emissions generated in a period of 1 year. Subsequently, the Theoretical Energy Potential (TE_P) of the estimated quantity of methane Emissions ($E_{meth.}$) is then calculated using Eq. 3:

$$TE_P = \frac{E_{meth.}}{\rho_{CH_4}} \times LHV_{CH_4} \times \Gamma_{BG.} \times \eta_{engine} \quad (3)$$

where, ρ_{CH4} is the density of methane at standard conditions of temperature and pressure taken as 0.00000072 Gg m^{-3} (Tchobanoglous and Kreith, 2002). LHV_{CH4} is the Lower Heating Value (LHV) of methane also taken as 9000 $kcalm^{-3}$ (Yedla, 2005) and the value of $\Gamma_{BG.}$ = 80% is the overall efficiency of the biogas production system (Kumar *et al*., 2014). The efficiency of internal combustion engine for biogas conversion to electricity is represented by η_{engine}. The value of η_{engine} varied with different size of electric power plants. A value of 25% has been used in small electric power engines and a range of 35-42% in large turbine systems (Hosseini and Wahid, 2014; Benito *et al*., 2015). In this study, 35% is adopted for η_{engine}.

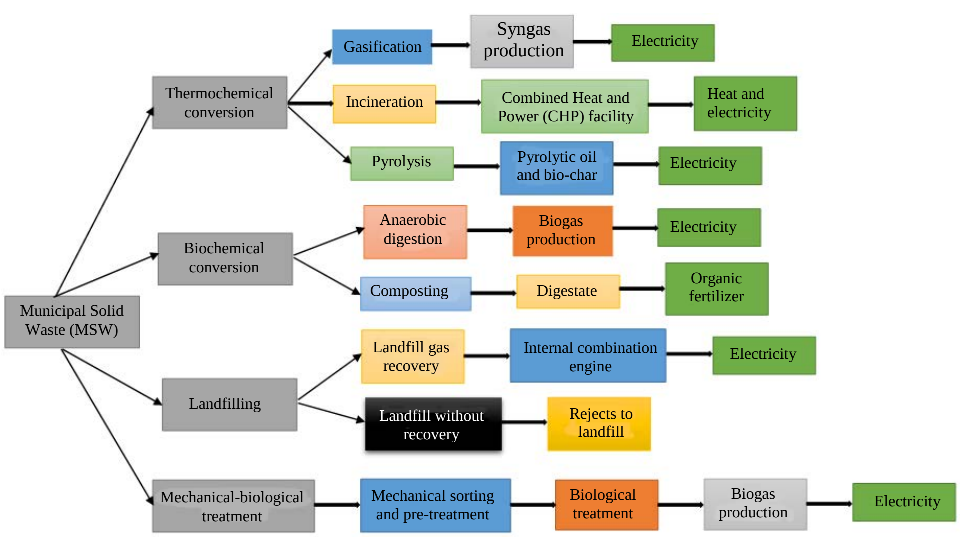

Fig. 2: Waste-to-energy conversion technologies

Table 1: Overview of different waste-to-energy technologies

Waste conversion technology	Advantages	Disadvantages
Anaerobic digestion	Treatment of biogenic component of MSW for biogas production	If operated inefficiently, anaerobic digestion system can cause odour irritation
	Biogas generated is a source of clean energy	Large scale of financial investment is usually required for commercial operation of anaerobic digestion systems
	Enhances sustainable management of biodegradable waste materials	
	Suppression of offensive environmental odour	The digestate can cause pollution of nearby rivers and streams when applied to agricultural crops in farm fields
	Liquid and fibrous manures generated can be used as fertilizer thereby increase revenue generation	
Incineration	Provides substantial reduction in the volume of wastes generated	It is quite expensive compare to other waste-to-energy technologies
	Waste processing and sorting activities are minimal	Ash waste generated from incineration plants is a source of environmental pollution
	The facility can be used for heat and power generation	Possibility of long-term problems due to burning of wastes without recycling
	Unlike landfilling, it saves on waste transportation expenses	
	Eliminates production of toxic chemical	
	Wide range adaptation to all weather conditions	
Gasification	It is a reliable waste-to-energy technology with environmental and economic benefits	Used for treatment of selected waste
		Engine corrosion due to formation of tar substances
	Higher energy recovery efficiency and lower quantity of pollutants compare to incineration	High processing temperature
	Affordable operating costs compare to traditional coal-fired power plants	
Landfill gas power projects	Universal waste disposal approach commonly used in every part of the world	It is characterized by lots of stricter regulations
	It has the tendency to produce landfill gas for energy generation	There is difficulty in reduction of the volume of MSW
	Easy implementation and affordable operational cost	Site location may be affected by the fear of secondary pollution issues
		There are tendencies to breed pests and diseases
		Public opposition to landfill sites could result in expensive logistic problem due to long distance away from where the wastes are generated

Table 2: Waste generation in Northern Nigeria geopolitical zones

Regional state capital	Cap/person/day (kg)	Monthly waste (tons)	Annual waste (tons)
North-East			
Bauchi	0.310	25,395	304740
Gombe	0.275	14,006	168072
Yola	0.280	25,365	304380
Damaturu	0.242	14,001	168012
Maiduguri	0.280	32,956	395472
Jalingo	0.250	14,253	171036
North-West			
Kano	0.560	156,676	1880112
Kaduna	0.230	44,433	533196
Katsina	0.320	18,452	221424
Sokoto	0.281	15,255	183060
Birnin-Kebbi	0.280	15,456	185472
Gusau	0.260	14,967	179604
Dutse	0.300	16,340	196080
North-central			
Lafia	0.210	13,956	167472
Lokoja	0.260	15,478	185736
Makurdi	0.280	32,956	395472
Ilorin	0.250	34,560	414720
Mina	0.246	14,989	179868
Jos	0.230	27,667	332004

Table 3: Waste generation in Southern Nigeria geopolitical zones

Regional state capital	Cap/person/day (kg)	Monthly waste (tons)	Annual waste (tons)
South-East			
Abakaliki	0.240	14,346	172152
Umuahia	0.230	15,895	190740
Enugu	0.310	16,009	192108
Awka	0.310	25,395	304740
Owerri	0.297	15,846	190152
South-West			
Lagos	0.730	255,556	3066672
Osogbo	0.240	14,957	179484
Ado-Ekiti	0.280	14,784	177408
Ibadan	0.310	135,391	1624692
Akure	0.320	15,089	181068
Abeokuta	0.360	36,116	433392
South-South			
Benin city	0.630	27,459	329508
Yenagoa	0.230	14,246	170952
Calabar	0.260	15,248	182976
Port Harcourt	0.700	117,825	1413900
Asaba	0.280	15,950	191400
Uyo	0.253	16,112	193344

Table 4: Waste generation in some selected important Nigeria cities

Regional state capital	Cap/person/day (kg)	Monthly waste (tons)	Annual waste (tons)
Major cities			
Aba	0.310	64,347	772164
Onitsha	0.700	84,137	1009644
Abuja	0.281	14,684	176208

RESULTS AND DISCUSSION

Waste characterization: From the field survey, there are six basic sources of waste materials in the country as shown in Table 5. The composition of different category of wastes are shown in the table. Wastes could be biodegradable or non-biodegradable and it could be further classified into hazardous and non-hazardous. MSW is a mixed up of traces of different materials: papers, textiles, plastics, water sachets, glasses, metals, e-wastes, food and garden wastes and other organic materials. In the concept of waste-to-energy, only the biodegradable and non-toxic component of environmental wastes can be utilized. The fractional composition of the MSW categories in percentage of the sorted out weight is shown in Fig. 3. The understanding of this fractional composition is very important in order to determine the suitable method of waste-to-energy management.

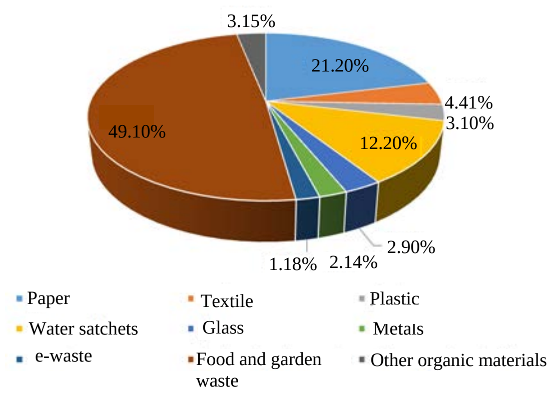

Fig. 3: MSW fractional composition in Nigeria Researcher's Field Survey, 2018

Estimated energy potential: The presence of biodegradable materials in MSW is responsible for free emissions of methane into the atmosphere. Methane has more than 20 times global warming potential than carbon dioxide. This is why uncontrolled landfill sites are potential locations for GHG emission problems. Since, methane is the main constituent gas of the emissions from potential landfill sites, therefore, the gas can be captured, optimized and burned for power generation with much lower impact on climate change. The results of mass of methane emissions and their corresponding theoretical energy potential are presented in Table 6-8. In Table 6, the results for the three northern geopolitical zones are merged for ease of data presentation. In the North-Eastern geopolitical zone, the capital city of Maiduguri exhibited the largest potential of 13.61 g and 199.3 TJ of mass of methane emission and theoretical energy potential respectively. The city of Yola and Bauchi also demonstrated substantial energy potential with the same value of 153.5 TJ. In the North-West geopolitical zone, both the potential of methane emission and the corresponding theoretical energy for the city of Kano is conspicuously high. The value of 947.3 TJ calculated for Kano is greater than the sum of the total potential of other states in the same geopolitical zone. In the North-central zone, the cities of Makurdi, Jos and Ilorin show greater potentials compare to Mina, Lokoja and Lafia. The scenario of MSW generation in the country is dependent on the population of inhabitants, economic potential and agricultural activities in the geopolitical region. However, in the overall regional strength, the potential of North-East is 761.6 TJ of energy while North-West has 1703.6 TJ. The North-central geopolitical zone gives a total potential of 843.9 TJ. A total of 609.67 Gg by mass of methane emission in all the geopolitical zones gives an estimated 10,596 TJ of electrical energy.

Table 7 shows the result of methane emission and their corresponding theoretical energy potential in the Southern Nigeria geopolitical zones. In the South-East, Awka exhibited the highest energy potential of 153.6 TJ but the lowest potential is calculated for Abakaliki which is 86.7 TJ. Lagos in the South-West showed the highest overall energy potential in the country with a value of 1545.2 TJ.

The next highest energy potential of 818.7 TJ in the South-West region is presented by Ibadan while the city of Abeokuta occupies the third position in the region with the potential of 218.3 TJ. In the South-South geopolitical zone, the scenario is that the city of Port Harcourt takes the lead in energy potential with a value of 712.4 TJ whereas Benin city followed with a potential of 166.1 TJ of electrical energy. In Table 8, the cities of Aba, Onitsha and Abuja have 1111.7 TJ, 1453.5 TJ and 88.7 TJ, respectively.

Table 5: Characterization of waste materials in Nigeria (Researcher's Field Survey, 2018)

Source of wastes	Waste generation activities	Characterization of waste components
Agricultural wastes	Crop production, forestry and animal husbandry	Livestock manures, slaughterhouse wastes, waste milk, animal slurry, postharvest crop residues, forest trims and dry wood wastes
Domestic wastes	Household activities	Household leftover food, papers, glasses, food cans, textile materials, waste water and plastics wastes
Industrial wastes	Industrial manufacturing processes, demolition works, construction activities and food processing	Construction garbage, demolition debris, chemical wastes, plastic materials, pulp and papers, waste water, textile materials, leather products and food processing, air discharges, scrap metals and hazardous wastes
Institutional wastes	School and office activities	Papers, glasses, food wastes and stationaries
Natural wastes	Natural activities carcasses of animals	Leaves, tree trims and branches, naturally disperse seeds and
Commercial waste	Restaurants cooking activities, business premises, hotels and activities of various commercial services	Pulp and papers, plastic waste, waste water and food wastes

Table 6: Methane emissions and the corresponding theoretical energy potential in Northern Nigeria geopolitical zones

Regional state capital	Annual waste (tons)	Methane emission Emeth (Gg)	Theoretical energy potential (TJ)
North East			
Bauchi	304740	10.48	153.5
Gombe	168072	5.78	84.6
Yola	304380	10.47	153.3
Damaturu	168012	5.78	84.6
Maiduguri	395472	13.61	199.3
Jalingo	171036	5.89	86.3
NorthWest			
Kano	1880112	64.69	947.3
Kaduna	533196	18.35	268.7
Katsina	221424	7.62	111.6
Sokoto	183060	6.30	92.3
Birnin-Kebbi	185472	6.38	94.4
Gusau	179604	6.18	90.5
Dutse	196080	6.75	98.8
North central			
Lafia	167472	5.76	84.3
Lokoja	185736	6.39	93.6
Makurdi	395472	13.61	199.3
Ilorin	414720	14.27	208.9
Mina	179868	6.19	90.6
Jos	332004	11.42	167.2

Table 7: Methane emissions and the corresponding theoretical energy potential in Southern Nigeria geopolitical zones

Regional state capital	Annual waste (tons)	Methane emission E_{meth} (Gg)	Theoretical energy potential (TJ)
South East			
Abakaliki	172152	5.92	86.7
Umuahia	190740	6.56	96.1
Enugu	192108	6.61	96.8
Awka	304740	10.49	153.6
Owerri	190152	6.54	95.8
South West			
Lagos	3066672	105.52	1545.2
Osogbo	179484	6.18	90.5
Ado Ekiti	177408	6.10	89.3
Ibadan	1624692	55.91	818.7
Akure	181068	6.23	91.2
Abeokuta	433392	14.91	218.3
South-South			
Benin city	329508	11.34	166.1
Yenagoa	170952	5.88	86.1
Calabar	182976	6.30	92.3
Port Harcourt	1413900	48.65	712.4
Asaba	191400	6.59	96.5
Uyo	193344	6.65	97.4

Table 8: Methane emissions and the corresponding theoretical energy potential in some selected important cities in Nigeria

Regional state capital	Annual waste (tons)	Methane emission (Gg)	Theoretical energy potential (TJ)
Major cities			
Aba	772164	26.57	1111.7
Onitsha	1009644	34.74	1453.5
Abuja	176208	6.060	88.7

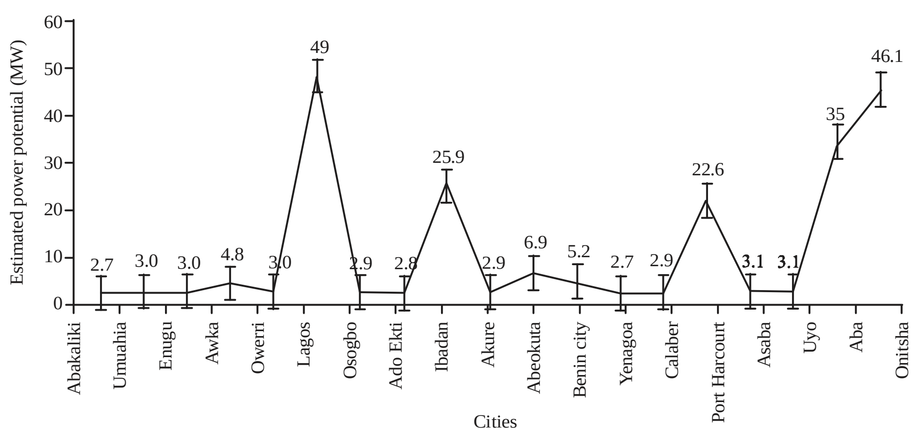

Fig. 4: State capitals in Northern geopolitical zones including the city of Abuja

Furthermore, the results of estimated power potential of the methane emissions from the landfill sites in the regional state capitals are shown in Fig. 4 and 5. The trend of the potential of power generation in the capital cities varies from one city to another depending on the volume of waste produced. A careful glance at the figures reveal that more states in the southern geopolitical zones have more potential capability to produce electricity from their landfill sites compare to the Northern regional states. The variation is as a result of the difference in the economic activities in each of the state. In Fig. 4, Kano metropolis shows the highest potential of 30 MW of electrical power. This is due to the fact that the city has the largest population in the entire regional states of Northern Nigeria couple with its vibrant economic activities. Obviously, this potential is not comparable to the city of Lagos (49 MW) in the South-West geopolitical zone. Aba and Onitsha are major economic cities in the South-Eastern Nigeria. The electric power potential of 35 MW and 46.1 MW calculated for Aba and Onitsha,

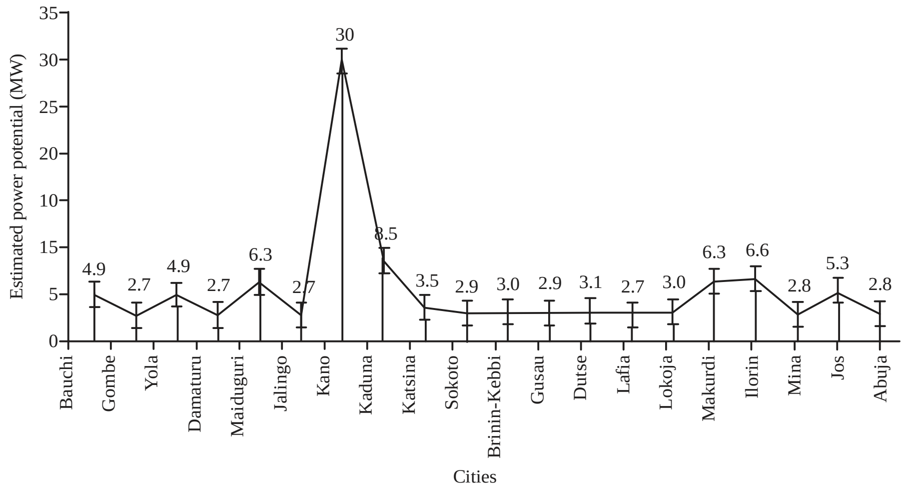

Fig. 5: States in Southern geopolitical zones including the cities of Onitsha and Abia

respectively are expected considering the economic strength of the cities. In Fig. 5, the estimated power potential of 25.9 MW and 22.6 MW calculated for Ibadan and Port-Harcourt, respectively can be justified based on their economic potential as well. While the city of Ibadan is obviously the largest city in the country, that of Port-Harcourt has vibrant commercial activities being the capital city of an oil producing state. A total of 335.2 MW power is estimated for all the six geopolitical zones including the three other major cities considered in this study.

CONCLUSION

This study presents the potential of methane gas for power generation in landfill sites located in the major cities of all the 36 states of the Federal Republic of Nigeria. The scope of the study also covers the nation's capital city (Abuja) and two other important economic cities (Aba and Onitsha). Methane gas in the waste dumping sites can be captured for small scale distributed power generation. This will not only combat the challenge of climate change but the problem of energy crisis in the country. A total potential of 335.2 MW of power generation is estimated which indicates that the country has a reasonable potential of electricity generation from MSW dumping sites. In furtherance, findings also reveal that the organic fraction of MSW in Nigeria has a larger share of the total waste generation which is also an indication that production of biogas for energy is quite promising. Production and application of biogas methane for power generation grants the opportunity for sustainable development and socioeconomic benefits. Other major benefit includesviable management of wastes through reduction in explosion of odours from landfills. Utilization of methane gas from landfill for power generation has been exploited in many developed and developing countries. In Nigeria, methane generation in landfill sites is expected to rise just like the situation in other countries due to growth in population and increasing socioeconomic activities. Conclusively, LFG capturing and optimization for power generation seems to be a good future option for sustainable energy and environmental friendly mechanism approach in the country.

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