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Review

Energy production potential of organic fraction of municipal solid waste (OFMSW) and its implications for Nigeria

Charles C. Ajaero[1], Chukwuebuka C. Okafor[1,*], Festus A. Otunomo[2], Nixon N. Nduji[1] and John A. Adedapo[1]

[1] Center for Environmental Management and Control, University of Nigeria, Enugu Campus, Enugu, 410001, Nigeria
[2] Nuclear Science and Engineering, Department of Engineering, North-West University, Potchefstroom Campus, 11 Hoffman Street, Potchefstroom, South Africa

* **Correspondence:** Email: chukwuebuka.okafor.pg01845@unn.edu.ng.

Abstract: The issue of climate change and management of municipal solid waste (MSW) necessitates transition to renewable energy, including bioenergy. This work assessed energy production from organic fraction of municipal solid waste (OFMSW) in the thirty-six state capitals and Federal Capital Territory (FCT), Abuja, Nigeria. Secondary research method (qualitative and quantitative analysis) was adopted. The four valorization methods considered were incineration, anaerobic digestion (AD), landfill gas-to-energy (LFGTE) and densification. MSW and OFMSW generation rate (kg/cap/day) for the thirty-six state capitals and the FCT, Abuja were obtained. The paper estimated that about 4.7 million tons per year (TPY) of OFMSW is generated in the 37 cities. Daily OFMSW generation ranges from 10416 tons per year (TPY) in Damaturu, to 1.6 million TPY in Lagos. The estimates show that about 1.82 billion Nm^3 of biogas could be obtained from anaerobic digestion (AD) of OFMSW generated in the cities each year; about 984 Gg (1085688 tons) of methane can be recovered from the landfill gas technology, while drying and densification will produce about 1.82 million tons of solid fuel. Based on secondary sources, the cost per ton waste and emissions (kg/ton) processed were also presented.

Keywords: energy production; organic municipal solid waste; renewable energy; waste management; sustainability; Nigeria

1. Introduction

MSW management is a challenging and common problem in urban areas of developing countries. Only a small fraction (41%) of the MSW generated in Nigeria are collected for disposal to landfills or dumpsites. The others that are not collected are carelessly disposed to the environment (open-dumping, burying, etc.) by households and businesses. Most often, the collected and uncollected MSW are burned. Thus, the there is growing focus on valorization of MSW [1,2] (especially organic fraction of MSW, OFMSW) for energy production. The major component of OFMSW is food waste. Food waste comprises of kitchen and food processing waste. It varies across different locations [3]. In Nigeria, the pursuit for reliable and adequate power supply has increased attention on renewable energy generation, which includes bioenergy. Bioenergy provides sustainable energy, which utilizes locally available resources as feedstock for energy generation [4]. Poor energy supply is another challenge facing Nigeria. Waste management and energy supply issues are made worse by the high population growth rate and inadequate investment [2]. Only 57.7% Nigerians have access to electricity, while it is 99.8% in Egypt, 91% in Morocco, 86% in South Africa and 78.3% in Ghana [5]. Per capita electricity consumption in Nigeria is 156 kWh, which is very poor when compared to other developing countries, such as Venezuela (3413 kWh), Ghana (309 kWh) [6] and Ivory Coast (174 kWh). These has led to great dependence on the use of domestic generators and greenhouse gas (GHG) emissions. Since demand heavily exceeds supply, a renewable energy (RE) system centered on obtainable resources is critical to improve energy supply. The current waste management method contributes to GHG and other pollutants emissions. Pollutants, such as dioxins, furans and polyaromatic hydrocarbons (known carcinogen), heavy metals, particulate matter (10), soot and smoke, etc., affect public health in a country that has a very poor health care system. Even when they are disposed to the landfills or dumpsites, biodegradation of the MSW leads to methane emissions, leachate pollution of soil, surface and groundwater. It is estimated that CH_4 emissions from waste disposal in Nigeria was 491000 tons in 2015. This is estimated to reach 670000 tons by 2030 [7].

The factors driving valorization of MSW for energy production, include climate change and other environmental challenges, energy diversification and access, waste management and policies supporting sustainability [2]. There are more than 800 waste-to-energy (WtE) plants in 40 countries around the world. They utilize around 11% of the MSW generated globally. The WtE plants generate roughly 429 TWh of electricity [1]. It is estimated that WtE will decrease by between 75–84% of the global warming potential of Nigeria's waste management [8]. The waste, which is hugely available in Nigerian cities, can be considered viable for energy valorization. The valorization will aid in reducing GHG emissions [1,2]. Accordingly, the major aim of this paper is to illustrate the energy potential of waste generated in Nigeria from different recovery methods.

Many works have been done on energy valorization from MSW in different cities or states of Nigeria—Ilorin [1,9]; Lagos and Abuja [10]; Port Harcourt [11]; Lagos, Port Harcourt, Abuja, Ibadan, Kano, Makurdi and Nsukka [12]; Osogbo [13]; Lagos [14]; 12 cities [8]; Anambra [15]. Ngumah et al. [16] and Suberu et al. [17] worked on biogas production potential from organic waste. However, the present work focused solely on OFMSW. This is because energy treatment of other MSW fraction, such as plastics, have serious environmental and health implications [2]. These are the gap the work intends to fill. This study used available OFMSW generation data (secondary data) for each of the state capitals to estimate energy potential from different technologies. The energy potential in megajoule (MJ), kWh or MWh were also estimated from the amount of OFMSW generated in the cities. The four technologies (incineration, anaerobic digestion (AD), landfill gas-to-energy (LFGTE) and densification) were chosen based on their viability, advanced development and feasibility for Nigeria, a developing country [1,2,18,19]. Specific objectives of the paper are (i) estimation of OFMSW generation; (ii) energy recovery potential from the estimated OFMSW generation; (iii) comparison—advantages and disadvantages; cost and environmental (emissions) of the different recovery technologies; and (iv) discussion on implications for sustainability. This will support policy and decision-makers, and provide a body of knowledge to aid research developments and directions for future studies.

2. Methods

A search was conducted for a research paper comprising waste generation rate and composition of cities in the 36 states and FCT, Abuja, Nigeria. The search was based on the fact that cities are the hubs of socio-economic, political, educational, and religious developments in Nigeria. Comprehensive waste generation (kg/cap/day) for 36 state capitals and the FCT, Abuja, Nigeria was identified in Suberu et al. [17]. Suberu et al. [17] also categorized OFMSW of the cities. Population figures were obtained and projected for the recent year (2021). These were then used to estimate waste generation (TPY) for each of the city. MSW and OFMSW (as a fraction of MSW) are presented in Table 1.

Table 1. Waste generation and characterization in state capitals of Nigeria and FCT.

State capitals		MSW generation (Kg/cap/day)[1]	Population[2]	OFMSW (%)[1]
North-East	Bauchi	0.31	493810	64
	Gombe	0.27	280000	70
	Yola	0.28	392854	68
	Damaturu	0.24	88014	70
	Maidugiri	0.28	540016	66
	Jalingo	0.25	118000	70
North-West	Kano	0.56	2828861	51
	Kaduna	0.23	760084	63
	Katsina	0.32	318459	70
	Sokoto	0.28	427760	66
	Birnin Kebbi	0.28	125594	70
	Gusau	0.26	383162	71
	Dutse	0.30	153000	70
North-Central	Lafia	0.21	330712	70
	Lokoja	0.26	195261	70
	Makurdi	0.28	365000	66
	Ilorin	0.25	777667	70
	Minna	0.24	304113	68
	Jos	0.23	679000	57

Continued on next page

State capitals		MSW generation (Kg/cap/day)[1]	Population[2]	OFMSW (%)[1]
South-East	Abakaliki	0.24	271000	70
	Umuahia	0.23	359230	65
	Enugu	0.31	722664	58
	Awka	0.31	301657	60
	Owerri	0.30	501000	70
South-West	Lagos[+]	0.73	9113605	36
	Osogbo	0.24	550000	60
	Ado-Ekiti	0.28	308621	65
	Ibadan	0.31	2559853	61
	Akure	0.32	403000	60
	Abeokuta	0.36	449088	60
South-South	Benin City	0.63	1156366	54
	Yenagoa	0.23	352285	65
	Calabar	0.26	371022	68
	Port Harcourt	0.70	1005904	60
	Asaba	0.28	149603	60
	Uyo	0.25	305961	58
Abuja		0.281	776298	65

[1][17]; [2][20]; [+]Though Ikeja is the state capital of Lagos; the whole of Lagos State is highly urbanized. Thus, the use of Lagos in Suberu et al. [17].

2.1. Estimate of the cities' waste generation

The population data were based on the National Population Commission (NPC) census of 2006, which was the last conducted in Nigeria. The population of each state capital for the year 2021 was predicted from the 2006 counts using Eq 1:

$$H_{2021} = H_{2006} \left(1 + \frac{r}{100}\right)^{2021-2006} \quad (1)$$

where H_{2006} is the population of each state capital in 2006; r is the annual population growth rate for urban Nigeria, which averages 4.48% per annum for the fifteen-year period [21]). Eq 1 was used to calculate the recent (year 2021) population of the cities. The population was then used to estimate the amount of OFMSW generated, as shown in Eqs 2 and 3.

$$W_{OFMSW} = H_{2021} \cdot W_{MSW} \cdot \mathrm{Y} \ (kg/c/d) \quad (2)$$

$$W_{OFMSW} = \frac{H_{2021} \cdot W_{MSW} \cdot \mathrm{Y} \cdot 365}{1000} \ (TPY) \quad (3)$$

where W_{OFMSW} is mass of OFMSW, W_{msw} is mass of MSW generated and Y is percentage composition of organic waste as a fraction of total MSW generated. The value of W_{msw} and Y for each city is shown in Table 1.

2.2. Energy recovery methods

2.2.1. Incineration

Most studies on WtE in Nigeria focuse on incineration. This is because it does not require complex technology like other methods, such as anaerobic digestion, gasification and LFGTE [2]. Incineration involves burning of wastes, thereby reducing its mass by 70% and its volume by 90%. The process produces steam for electricity generation and cogeneration [14]. The energy potential of the organic portion of MSW is expressed as [1] (Eq 4).

$$EP_{MSW} = LHV_{MSW} \times W_{MSW} \times \frac{1000}{3.6} \text{ (kWh)} \quad (4)$$

where EP_{OFMSW} is the energy potential from the MSW, W_{OFMSW} is the mass of organic portion of MSW (tons) and LHV_{OFMSW} is the net low heating value of OFMSW (MJ/kg). The converting ratio is 1 kWh = 3.6 MJ. The paper assumes that 100% of the estimated OFMSW is valorized for energy generation. The average net heating value (LHV_{OFMSW}) of urban OFMSW in low- and middle income countries (Africa) considered for energy production is 17 MJ/kg [22]. A solid waste should have a calorific value (LHV) of 7.5–17 MJ/kg before they can be considered a fuel source [2,23]. The OFMSW, therefore, can be considered a valuable source of fuel since they meet the criteria.

The electrical power potential was calculated using Eq 5 (adapted from Ibikunle et al [1]):

$$EPP_{OFMSW} = 277.8 \times LHV_{OFMSW} \times \frac{W_{OFMSW}}{24} \times ɭ \quad (5)$$

where EPP_{OFMSW} is the electrical power potential (kW), 277.8 is the conversion ratio ($^{1000}/_{3.6}$) from MJ to kWh (1 kWh = 3.6 MJ); W_{OFMSW} (tons) is the weight of OFMSW, LHV_{OFMSW} is the net low heating value of the OFMSW (MJ/kg) and ɭ is the conversion efficiency.

Power to grid *(GP)* is calculated uing Eq 6 [1] as follows:

$$GP = EPP_{OFMsw} \times ɭ_g \times ɭ_p \times \frac{1}{1000} \ (MW) \quad (6)$$

where $ɭ_g$ is the generator efficiency (usually taken as 90%) and $ɭ_p$ is the transmission efficiency (usually around 75% of turbine output [9].

2.2.2. Anaerobic digestion

In anaerobic digestion, volatile solids (VS), which indicate the organic content of the feedstock, determine the amount of biogas that can be produced. The potential biogas yield from a waste stream is usually expressed as the biomethane potential (BMP). BMP indicates a measure of the amount of (CH_4) that can be generated per unit of VS of a feedstock. The potential amount of biogas B_v in Nm^3 that can be generated from AD is calculated in Eq 7 [22].

$$B_V = WS_m \times \frac{TS_m}{100} \times \frac{VS_m}{100} \times \frac{VS_D}{100} \times BMP \ \frac{100}{60} \quad (7)$$

where WS_m is the amount of waste stream (OFMSW) in tons, TS_m is the total solids content as a fraction of the total wet mass expressed in percentage, VS_m is the amount of VS as a percentage of total solids, VS_D is the percentage rate of VS degradation, which gives the portion of VS that is biodegraded into biogas during the anaerobic digestion proces; and *BMP* is the biomethane potental of the waste stream (organic) in Nm^3 CH_4/ton. Usually, CH_4 acounts for 60% of the biogas generated from the AD process [22,24].

The energy content (E_c) in biogas in MJ and kWh are expressed in Eqs 8 and 9, after Ddiba et al. [22]:

$$E_c(MJ) = B_V \times 21.6 \tag{8}$$

$$E_c(kWh) = B_V \times 6 \tag{9}$$

2.2.3. Landfill gas-to-energy

Decay of organic wastes produces CH_4, CO_2 and insignificant amount of non-methane volatile organic compounds (NMVOCs). The OFMSW is degraded by aerobic bacteria until O_2 is exhausted. Adopting the default IPCC [25] method, the amount of CH_4 emitted from waste disposal sites, which can be captured for energy uses, are expressed in Eq 2. This is expressed in Eq 10.

$$Q = \left(MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} - R\right)(1 - OX) \tag{10}$$

where Q is total CH_4 emissions in Gigagrams per year (Gg/yr), MSW_T is total organic waste generated (Gg/yr), MSW_F is fraction of organic waste disposed to landfill, *MCF* is methane correction factor (a fraction), DOC_F is dissimilated organic fraction (portion converted to LFG), F is a fraction of CH_4 in LFG, R is recovered (Gg/yr), $^{16}/_{12}$ is molecular weight ratio of CH_4 and C and is the oxidation factor (a fraction). The paper assumes that the entire OFMSW are disposed to the landfill, hence MSW_F is taken as 1. The default value of *MCF* is 1 (for managed anaerobic SWDS), while the default value for *DOC* is 0.5. Since the biodegradation of *DOC* is not complete even for OFMSW, the DOC_F default is usually accepted as 0.77. The quantity of CH_4 in LFG is usually around 50%, therefore, F is 0.50. The default value of R is usually taken as zero, while the default for *OX* is 0.1 (for managed landfills with covered CH_4 oxidizing material) [26]. After IPCC [26], the method assumes that all the potential methane produced are released within the same year the OFMSW were disposed to the landfill.

1 m^3 of CH_4 has calorific value of 36 MJ [27,28]. With the assumed electrical conversion efficiency of 35%, 1 m^3 of methane will yield 10 kWh [28]. 1 m^3 is equivalent to 0.46454 ton (Cool conversion.com).

2.2.4. Drying and densification for solid fuel generation

In solid fuel production from OFMSW, the most important factor to consider is the calorific value or heating value. The value denotes the amount of energy embodied in the waste stream. The amount of solid fuel in tons (F_m) that can be produced from the OFMSW (in tons) is expressed in Eq 11. Normally, the densification process has insignificant effect on the total mass of the waste stream being converted into solid fuel [22].

$$F_m = WS_m \times \frac{TS_m}{100} \tag{11}$$

The energy content in the solid fuel (E_f) in MJ, is calculated using Eq 12, while the energy content in kWh is obtained in Eq 13 [22].

$$E_f(MJ) = WS_m \times \frac{TS_m}{100} \times 1000 \times GCV \tag{12}$$

$$E_f(kWh) = E_f(MJ) \times 0.277778 \tag{13}$$

where WS_m is the amount of waste stream (OFMSW) in tons, TS_m is the total solids content as a fraction of the total wet mass expressed in percentage; *GCV* is the gross calorific value of the OFSMW, which is the same as *LHV* in MJ/kg TS; and 0.277778 is the constant for standard conversion of MJ to kWh. The calculated TS_m is 38.56% and the GCV (or LHV_{MSW}) is 17 MJ/kg [22]. The parameters used for the calculation for the different WtE methods are shown in Table 2.

Table 2. Parameters and values used for the computation.

Method	Factor	Values	Description	References
Incineration	LHV_{OFMSW}	17 MJ/kg	Average net gross calorific value of OFMSW for LMICs	[22]
	ɭ	30%	Power plant conversion efficiency (usually between 20% to 40%)	[1]
Landfill gas	MSW_T	-	Total organic waste generated (Gg/yr)	[26]
	MSW_F	1	OFMSW disposed to landfill	
	MCF	1	Methane correction factor fraction (for managed anaerobic SWDS)	
	DOC	0.5	Degradable organic carbon (Kg C/kg SW)	
	DOC_F	0.77	DOC fraction dissimilated	
	F	0.50	Fraction of methane in LFG	
	R	0	Recovered CH_4 (Gg/yr)	
	OX	0.1	Oxidation factor, fraction (for managed landfills with covered CH_4 oxidizing material)	
Anaerobic digestion	TS	28.90	Total solid	[22]
	VS	75	Volatile solid	
	TS_M	38.53	Total solids content as a fraction of the total wet mass (%)	
	VS_M	260	Amount of VS as a percentage of total solids	
	VS_D	60	Percentage rate of VS degradation	
	BMP	400	Biomethane potential	
Densification	Calculated TS_M	38.53	Total solids content as a fraction of the total wet mass (%)	Based on Ddiba et al. [22]

3. Results and discussion

3.1. The estimated OFMSW generation

The average per capita MSW generation for the cities is 0.313 kg/cap/day. OFMSW accounts for 64% of the total wastes generated. Figure 1 shows the estimated MSW and OFMSW generation of the cities (grouped by regions) and FCT Abuja.

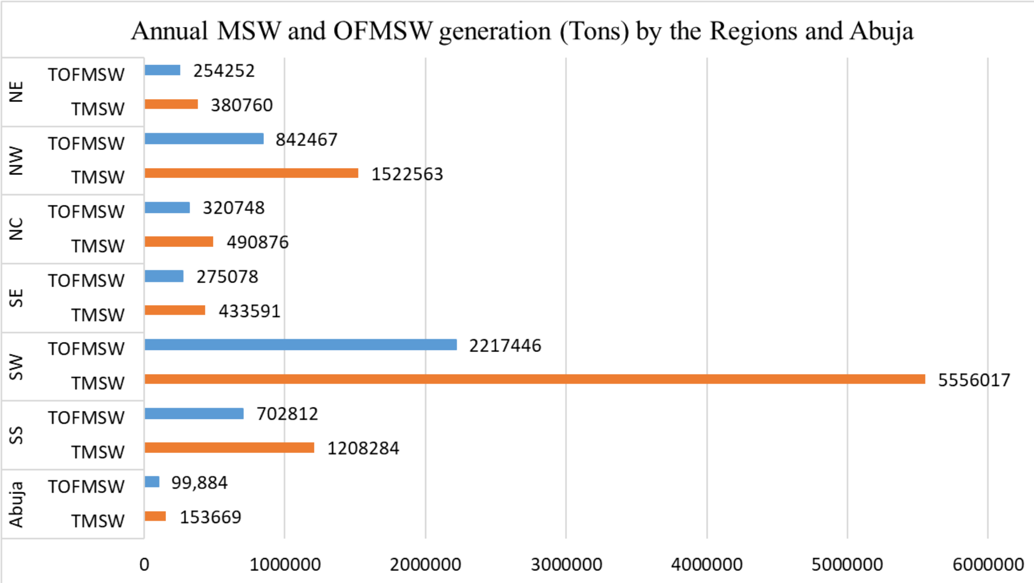

Figure 1. MSW and OFMSW generation (TPY).

As shown in Figure 1, the highest waste generation is obtained in Southwest Nigeria, followed by North-West region, South-South, North-Central, South-East and then the North-East. This is a factor of waste generation rate and population. South-West has the first and third most populous cities (Lagos and Ibadan) in Nigeria; while the North-West has the second most populous city (Kano). The South-South has the 4th and 5th most populous cities (Benin City and Port Harcourt) in Nigeria. Figure 2 shows the OFMSW generation (TPY) by the cities.

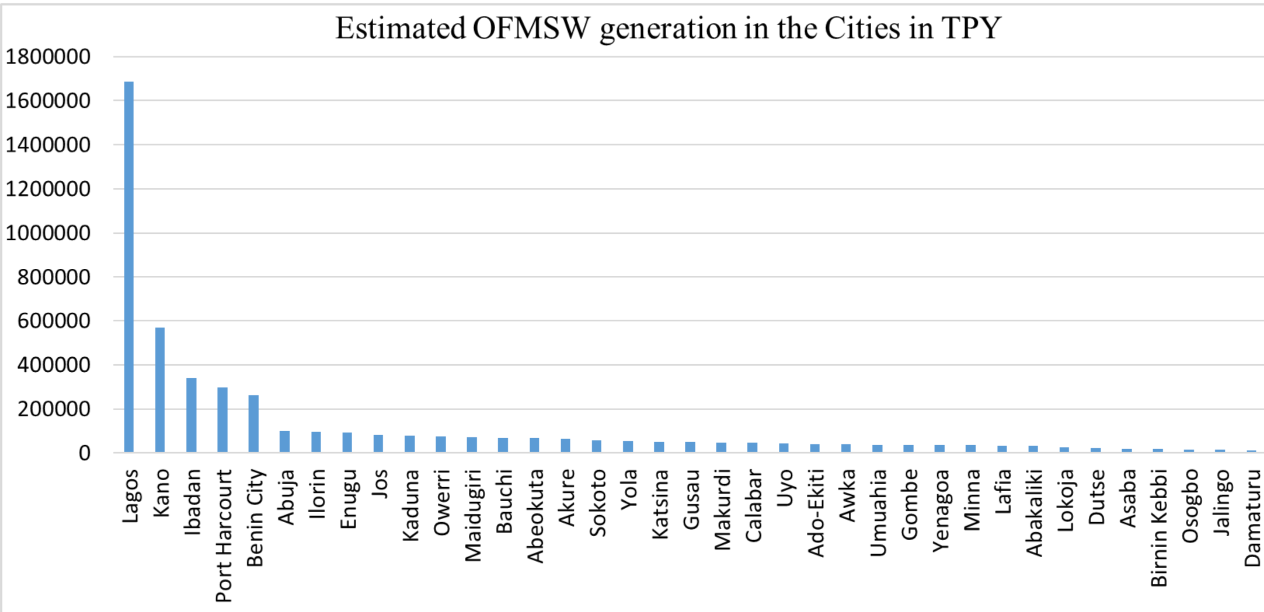

Figure 2. Estimated OFMSW generation in the cities (TPY).

As shown in Figure 2, the city with the least OFMSW generation (TPY) is Damaturu, while Lagos has the highest. The cosmopolitan nature of the most populous cities means more economic activities. This translates to comparative higher income potential and, consequently, more waste generation potential. Excluding Ibadan, which has 0.31 kg/cap/day, the other four most populous cities (Lagos, Kano, Benin city and Port Harcourt) have generation rates ranging from 0.56–0.73 kg/cap/day, with an average of 0.65 kg/cap/day. This is higher than the average of 0.27 kg/cap/day for the other 32 cities.

3.2. Energy recovery potential

The result in Table 3 shows that total energy potential from incineration of the OFMSW is about 22256114 MWh. In Table 4, up to 1.82 billion Nm^3 of biogas could be obtained from the AD of the more than 4.7 million tons of OFMSW generated in the cities each year. Employing the IPCC proposed method [25,26], Table 5 shows that about 984 Gg (1085688 tons) of methane can be recovered from the landfill gas technology. Drying and densification of the OFMSW will produce about 1.82 million tons of solid fuel (Table 6).

Table 3. Calculated energy and electrical potential of incinerating the OFMSW (per annum).

Regions	Calculated EP_{OFMSW} (MWh)	EPP_{OFMSW} (MW)	GP (MW) annual	GP (MW) daily
NE	1200703	15009	10131	28
NW	3978636	49733	33570	92
NC	1514766	18935	12780	35
SE	1299083	16239	10961	30
SW	10472110	130901	88359	242
SS	3319101	41489	28005	77
Abuja	471715	5896	3980	11

Table 4. Calculated biogas and energy potential from anaerobic digestion of the OFMSW.

Regions	B_V (Nm^3)	E_c (MJ)	E_f (kWh)	E_f (MWh)
NE	97806516	2112620743	586839095	586839
NW	324083248	7000198156	1944499488	1944499
NC	123386547	2665149407	740319280	740319
SE	105817935	2285667393	634907609	634907
SW	853014933	18425122546	5118089596	5118089
SS	270360271	5839781853	1622161626	1622161
Abuja	38423940	829957110	230543642	230543

Table 5. Calculated LFG and energy potential from the OFMSW LFGTE method.

Regions	Q (Gg)	Q (Tons)	Q (m^3)	E (kWh)	E (MWh)
NE	53	58573	126089	1260891	1260
NW	176	194084	417798	4179978	4180
NC	67	73893	159066	1590660	1590
SE	57	63371	136417	1364171	1364
SW	463	510845	1099680	10996680	10996
SS	147	161911	348540	3485400	3485
Abuja	21	23011	49535	495350	495

Table 6. Calculated solid fuel and energy production potential of the OFMSW densification.

Regions	F_m (Tons)	E_f (MJ)	E_f (kWh)	E_f (MWh)
NE	97963	1665375370	462604640	462604
NW	324602	5518244407	1532846895	1532846
NC	123584	2100932785	583592907	583592
SE	105988	1801787753	500496998	500496
SW	854382	14524493045	4034584629	4034584
SS	270794	4603490191	1278748298	1278748
Abuja	38486	654253791	181737310	181737

The energy potential (MWh) of the different methods of valorizing the OFMSW shows the following 22.2 million MWh/year (incineration); 10.9 million MWh/year (anaerobic digestion); 23370 MWh/year (landfill gas recovery) and 8.6 million MWh/year (densification for solid fuel). Comparatively, the energy potential of the different processes per ton of treated OFMSW shows the following—0.211 MWh/ton (incineration), 0.43 MWh/ton (AD), 0.55 MWh/ton (densified solid fuel) and 0.005 MWh/ton (LFG). Practically, the energy recovery from the OFMSW may be higher or lower than the calculated value, considering factors such as waste collection efficiency [6], chemical element composition, conversion efficiency, variation in waste composition, which affects the net low heating value [1,13], poor handling and long storage of the wastes ,which result in energy loss (biodegradation), plant capacity utilization [28], and other process characteristics, such as landfill management type, etc. For example, 1% increase in chemical hydrogen and nitrogen content (obtained via ultimate analysis) of the OFMSW decreases heating value by 30.2% and 620%, respectively [9]. Only 44% of the MSW generated in the country are collected [29], with the rest carelessly disposed of in the environment. Realistically, bioenergy recovery from OFMSW cannot supply the whole energy requirements of a city or Nigeria, as a whole, but it can help supplement the supply. The uncertainty in waste generation data in Nigeria means that true measure of energy potential estimate from OFMSW is still unknown in Nigeria [6].

3.2.1. Incineration

Our calculated energy potential via incineration (22256114 MWh) is similar to 26.7 million MWh/year (26744 GWh/year) in Somorin et al. [6], which assumes valorization of about 80% of the generated waste in the country. The average energy yield from incineration for mixed MSW is about 0.55 MWh/ton [30]. Our calculated value for incineration (0.211 MWh/ton of OFMSW) is lower than 0.55 MWh/ton because only OFMSW was considered. Different studies in Nigeria recorded the LHV (calorific value) of mixed MSW as 21.44 MJ/kg [12]; 23 MJ/kg [1], 22.14 MJ/kg [11]. Conversely, the net LHV for OFMSW (for LMICs) used in our work is 17 MJ/kg [22]. Our calculated yield (0.211 MWh/ton) fares fairly well with 0.313 MWh/ton recorded in Akinshilo et al. [14], and is much higher than 0.04 MWh/ton (organic) [31]. Energy potential via incineration for other waste streams were 0.36 MWh/ton (paper), 0.37 MWh/ton (textiles) and 0.96 MWh/ton (plastic) [31]. In the US, although biomass (organics) accounts for 61% of the incinerated wastes, they account for 45% of the recovered electricity. Conversely, the remainder (39%) of the incinerated wastes, which are mostly plastics, accounts for 55% of the recovered energy [32]. This indicates that energy recovery potential from waste streams, such as plastics, is higher than those of OFMSW. However, incineration of plastics (for energy recovery) has numerous environmental and health issues, such as metals, SO_2, NOx, dioxins and other toxic compounds emissions [2].

The advantages of incineration method over the others for a country such as Nigeria with poor waste management, are abatement of methane emissions and leachate pollution of water resources [1,13] produced by un-engineered open-dumps. It is more valuable when by-products, such as ash, are pre-treated and utilized for other processes, such as cement making. Incineration also reduces the amount of wastes going to landfills by 87%. In the US, only 12% of the 292 million tons of MSW generated in 2018 were incinerated in 65 WtE plants. This represents 25 million tons of combustible MSW, which generated 13.5 billion kWh of electricity [32]. Other works show that incineration of MSW will meet 15% or 41 MW daily needs for Ilorin [1], 10000 MW per day for Lagos of the electricity needs of the people [14], 545 MW for Aguata LGA (in Anambra State) [15]. The potential viability of incineration recovery method has been shown by [1,2,6,13].

To optimize incineration plant performance and sustainability, waste supply should not be lower than 50000 tons per annum (137 tons/day); minimum net LHV should be at least 6 MJ/kg; containing moisture content lower than 50%; and the waste compositions should not vary more than 20% at any time [6]. Figure 3 shows Nigerian state capitals generating less than 137 tons/day of OFMSW, based on our calculation.

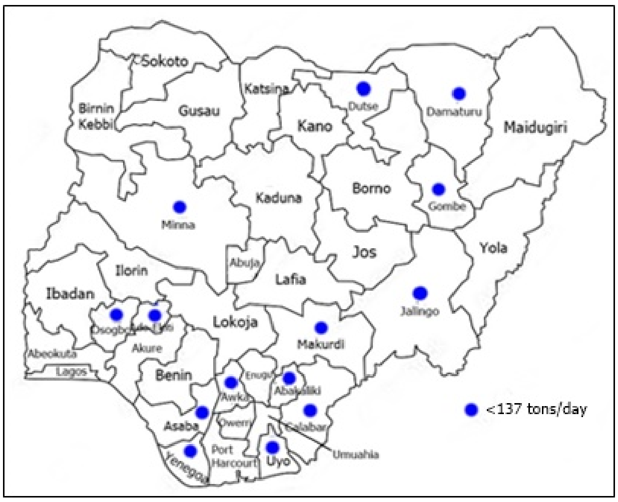

Figure 3. Nigerian capitals generating less than 137 tons/day.

As shown in Figure 3 about 60% of the 37 cities meet the waste generation rate of 137 tons/day. This indicates the potential of the method for energy generation in Nigeria.

3.2.2. Anaerobic digestion

Our calculation shows that about 384 Nm^3 of methane is obtained per ton of OFMSW. This is higher than 200 Nm^3 per ton of biomass obtained in experimental studies. The reported rate of CH_4 generation in industrial AD reactors ranges from 40 to 80 Nm^3 [30]. Our calculated 0.43 MWh per ton of OFMSW is consistent with those obtained in other studies—0.473 MWh/ ton of food waste [27] and 0.405 MWh/ton of FW [33]. AD is a cost-effective biotechnology for the treatment of OFMSW and bioenergy (biogas, electricity and heat) production. Apart from biogas produced, organic residue (digestate) produced by the process is rich in macro nutrients and can be used to produce organo-fertilizer [9,27]. The potential CH_4 produced by managed LFG method can be recovered and utilized as a source of renewable energy. It will aid mitigate GHG emissions and pollution occasioned by improper waste management method in the country. OFMSW in Nigeria consists mostly of food wastes, which have a high moisture content around 48.7%. The high moisture content favors landfill LFG (and methane) production [13]. OFMSW in landfills go through anaerobic digestion to generate methane. The amount of gas produced is influenced by the management method used in the landfill. Therefore, to adopt this method, the cities should develop a landfill with organized dumping; that are covered daily; leachate collection and treatment installations [7]. The capture of the LFG (including the CH_4 constituent) is an important renewable energy resource, which will help reduce methane emissions. The method will, therefore, reduce global warming and the effect of climate change. Combustion of CH_4 gas via Organic Rankine Cycle or biogas generator generates electricity to power small and medium scale industries, commercial enterprises and households [13]. Harnessing this potential renewable energy resource will add more power to the grid or off-grid.

3.2.3. Landfill gas-to-energy (LFGTE)

Our calculated methane generation potential of 0.50 m^3 CH_4 /ton MSW (232 kg CH4/ton OFMSW or 0.232 ton CH_4/ ton OFMSW at −164 °C and density of 464.54 kg/m^3) is greater than the experimental yield obtained. The amount of LFG generated is 213 Nm^3 CH_4 (or 0.153 ton CH_4) for each dry ton of biomass [30]; 50 to 100 kg CH_4 /ton of MSW [12]. This is related to the factors used in the calculation. We assumed MSW_F = 1, i.e the whole waste generated is disposed to landfill, while it is 0.74 in Amoo and Fagbenle (2013). We also assumed *MCF* is 1 (for managed solid waste disposal sites), while it is 0.4 (shallow unmanaged landfill) [12]. A measure of the methane generated in landfills can be recovered and utilized as a renewable energy source. Long term methane recovery from 25 landfills in California shows that only 34% of the methane generation are captured, while 66% are lost. For a LFG collecting landfill, the average depth is 28 m in the US. About 50% of the potential methane in a collection of MSW can be generated in one year of residence time in a landfill [30]. In the US, the regulation mandates collection of gas from the landfill, even after its full and closed. They are also required to treat the discharged effluents and monitor the environment for 30 years [30]. This adds to the cost of LFGTE as producers, or owners of the landfill will continue to ensure quality control even after the landfill has been closed and ceases to yield gas. However, comparatively, a LFGTE system requires low investment, and has capacity to process huge volumes of waste. It is also a rapid way of disposing waste [34]. Apart from tradable energy produced from the LFGTE, tipping fees is a financial support during the operational lifespan of the landfill. Tipping and/or collection fees has been a challenging issue across cities in Nigeria. The issue is one of the factors critically militating collection efficiency, since it funds the value-chain of waste collection and post-collection treatment.

3.2.4. Drying and densification

Organic wastes are challenging to handle, store and use in their usual state because of their high moisture content. Densified OFMSW can be used to produce either briquette or pellet, which have many domestic (heating and cooking) and industrial applications. In drying or torrefaction, OFMSW is heated to a temperature of 250–300 °C [35]. Densification into pellets or briquettes increases the bulk density of OFMSW from around 40–200 kg/m^3 to a compact density of 600–1200 kg/m^3 [36]. Briquetting is the compression of a material into a solid product of greater bulk density, low moisture content and even dimension and shape, which allows utilization as fuel similar to wood or charcoal [37]. Burning 1 kg of briquettes in a stove yields 7.7 MJ/kg of useful energy. Comparatively, burning 6.11 kg of fuelwood in a fuelwood stove yield 1.3 MJ/kg. It therefore takes 6 times the fuelwood to provide equivalent useful energy to that of briquette. Further, 0.32 kg of kerosene will produce equivalent calorific (energy) output of 1 kg of briquette [38]. Kerosene is highly costly in Nigeria, for an average rural household. Fuelwood is one of the causes of deforestation in rural (and even among urban low-income households) in Nigeria. Accordingly, the use of densified biomass for energy production has both economic and environmental benefits. Globally, Nigeria has one of the highest rates of deforestation. In 2020 alone, Nigeria lost 97.8 kilohectares of forest. This is equivalent to 59.5 metric tons of CO_2 emissions. In total, the country has lost 96% of its ancient forests [39]. While urbanization and agriculture accounts for the majority of the leading causes of deforestation, fuelwood consumption is also a factor. About 50 million tons of fuelwood is consumed in the country per annum [16]. The high rate of deforestation (3.5%) leads to other ecological issues, such as loss of biodiversity and soil fertility, and the negative impact on ecosystem services (for example, carbon sink) they provide. Densification of OMSW (solid fuel) will aid in reducing deforestation and promoting public health. Acceptability and viability of densification is somewhat mixed [4] compared to the other technologies.

3.3. Comparison of the different valorization technologies

Biofuel is among the most expensive options (per kWh) for electricity production. While the average for solar PV is now 6 $/kWh, offshore wind (5.9 $/kWh) and combined cycle natural gas ($4.9/kWh), it is around 8.2–19.6 $/kWh for biogas (US Department of Energy, 2019). However, the price of the immediate gas obtained through AD is highly competitive to the price of natural gas [12]. Notwithstanding, the environmental trade-offs (carbon neutral) bioenergy promotes is attracting policy attention in the form of subsidies and credits. This makes it a competitive energy source [30,32,40]. The advantages and disadvantages of the different technologies are shown in Table 7; while Tables 8 and 9 shows the cost per capacity and emissions (Kg/ton of waste processed).

Table 7. Advantages and disadvantages of the energetic recovery methods.

Method	Advantages	Disadvantages
Incineration[a,b]	Requires small land area Significantly reduces the volume of waste going to landfills	Requires high investment relative to landfill gas recovery method Flue gas and other pollutants production The heating value (LHV) of the waste cannot be too low
Anaerobic digestion	The digestate can be utilized as fertilizers[c] The digestate is a promising feedstock for renewable hydrogen production	Presence of inhibitory substances, such as NH_3, H_2S and heavy metals[d] Reaction of the element leads to acid formation, such as H_2SO_4 which corrodes equipment and engines Treatment and removal of the elements adds to the process cost Biodegradation kinetics is relatively slow[e]
Landfill gas-to-energy[a]	Requires low investment Capacity to process huge volume of waste Rapid way of disposing waste	Requires great expanse of land Secondary pollution via possible leaching contaminating groundwater; and leakage of methane emission to the air
Densification[f]	Have physical and chemical properties as woody and herbaceous biomass Biomass aerobically stable Hydrophobicity and homogeneity of product Improves particle size distribution, shape, volumetric and energy density, durability, handling and storage of densified fuel[f]	Though lower than fossils, requires proper control measures to capture emissions Slow commercialization because of challenges related to reactor design and final product quality Slower reaction time; and high energy condition for non-oxidative torrefaction

[a][34]; [b][1]; [c][41]; [d][3]; [e][18]; [f][42].

The WTE technologies have different costs and emissions. Tables 8 and 9 shows average costs and emissions for the different methods.

Table 8. Costs (EUR) for the different WtE technologies.

Method	Capacity (TPY)	Initial investment cost (million EUR)	Capital cost per ton (EUR)	O&M cost per Ton (EUR)	Net cost per Ton (EUR)
AD*	50000–150000	12–20	12–19	10–15	22–34
LFGTE*	390000–850000	5.3–6	0.8–1.4	0.3–0.8	6–7
Incineration*	150000	30–75	22–55	20–35	42–90
Densification+	20000	-	-	-	97 USD

*[19]; +[43].

Table 9. Emissions (Kg/ton of waste processed) for the WtE technologies.

Method	CO_2 (biogenic)	CH_4	H_2S	NH_3	NOx	NMVOC	CO
AD**	30	11.2	0.06	0.65	-	-	-
LFGTE**	133	48.4	-	-	-	-	-
Incineration**	562	-	-	0.01	0.49	0.012	-
Densification[++]	29	-	-	-	-	-	3

**[10]; [++] [35].

In order to decrease emissions from waste management and the different energy valorization methods, cities must consider a complex set of potential alternatives within a variety of environmental considerations, such as GHG emissions, air quality. [44] and economics. The emissions depend on plant conversion efficiencies, environmental conditions and context. In a prospective lifecycle assessment (LCA) environmental impact; the following impacts were considered: abiotic depletion potential (ADP), global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP) and photochemical oxidation potential (POCP) for three WtE methods. AD had the least environmental impact, except for POCP. LFGTE had the greatest environmental impact, except for ADP and HTP. Incineration has the lowest POCP. The highest environmental impact recorded for LFGTE is related to loss of about 50% of the generated methane [10]. Improper management of OFMSW emits methane to the atmosphere, which has a GWP 23 times that of the same amount of CO_2 [30]. Even though CO_2 emission is highest for incineration, the GWP of CH_4 recorded in LFGTE negates its relative impact compared to LFGTE. The GWP of CH_4 is between 28 to 34 times that of CO_2 in a 100-year period; and 84–86 times for a 20-year period. The anaerobic decomposition of OFMSW in LFG and AD produces methane. Leachates seepage or leakage in landfill facility is also likely to occur in landfills. Amoo and Fagbenle [12] shows that AD is a preferred method to landfilling, because of its high decomposition potential and biogas production. As shown in Tables 8 and 9, torrefaction and densification have the least CO_2 emissions. However, the net cost per ton of processed waste is highest for densification, followed by incineration. The total cost per ton of treated waste is lowest in the LFGTE process. Notwithstanding, the relatively lower emissions from the WtE methods, increasing energy conversion efficiencies of wastes lead to reduction in emissions from MSW management. An example, incinerating MSW for electricity and heat production in Kocaeli, Turkey leads to avoided emissions of around 890000 tCO_2e/yr or net savings (global warming factor, GWF) of −0.94 tCO_2e per ton of incinerated MSW; 179000 tCO_2e/yr or GWF of −0.274 tCO_2e/ton MSW for LFG [45].

Energy consumption (kWh) for production of biofuels (per ton of processed wastes) shows the following: densification (128 kWh/ton) [46], incineration (78 kWh/t), AD (8 kWh/t) and 14 kWh/t (LFGTE) [10]. AD has the lowest energy consumption, followed by LFGTE. The high-pressure operation, and relatively higher energy consumption for pre-drying and intermediate heating stage, contributes to the identified high cost of drying and densification method [46]. AD shows consistent desirability in all the factors considered. As shown in Tables 8 and 9, it has the second lowest CO_2 emissions, after densification. It has the second lowest initial investment cost and net cost per ton, after LFGTE. It has the second energy potential (MWh) per ton of treated OFMSW, as shown in our computation, after densification. Densification has the highest net cost and energy consumption (kWh) per processed ton.

4. Implications for sustainability

It is estimated that open burning of uncollected MSW generated in Nigeria emits between 798 to 1197 kilotons of CO_2-eq each year, representing between 0.3–0.6% of the entire waste burned globally [47]. Factoring this in. those collected will increase the tons emitted. Figure 4 shows the benefits of energy recovery from OFMSW.

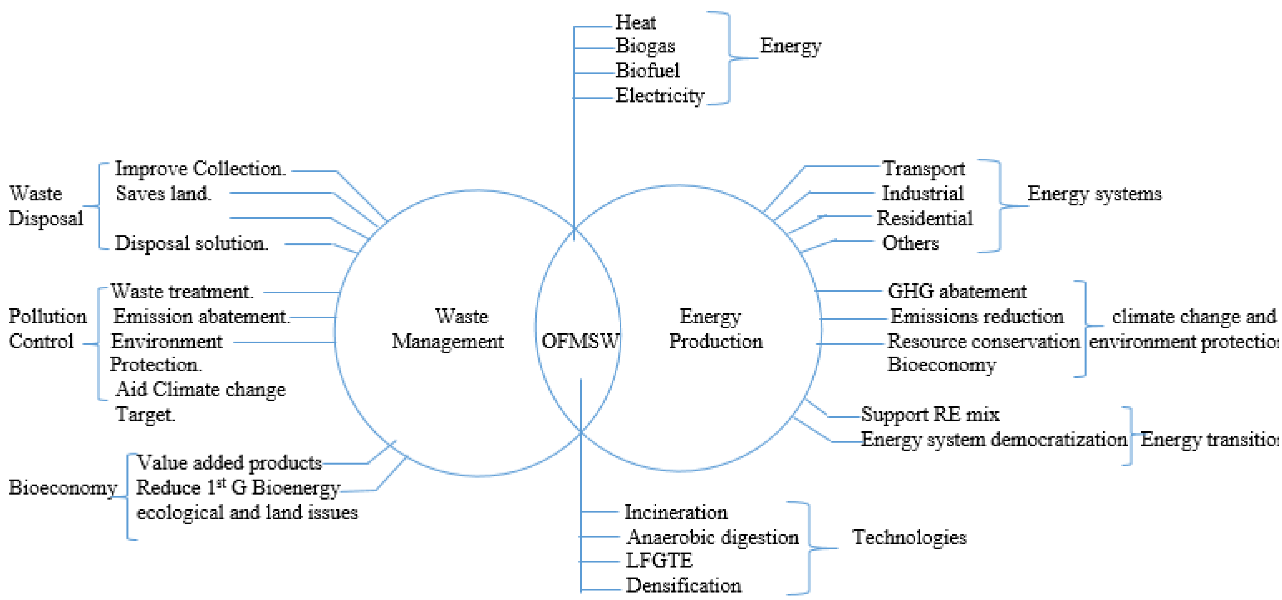

Figure 4. Implications of OFMSW energy valorization.

As shown in Figure 4, energy recovery from waste encompasses various SGDs—SDG6 (clean water and sanitation), SDG number 7 (affordable, reliable and modern energy), 8 (decent work and economic growth); 11 (sustainable cities and communities), 12 ("sustainable consumption and production patterns") and 13 ("urgent action to combat climate change and its impacts") [2,22]. Energetic recovery of waste generated in Nigeria will reduce global warming potential (GWP) from the country's waste management sector by around 80% [8]. From a technical approach, the analysis in the paper shows a number of opportunities: socioeconomic and environmental.

Constraints to wide adoption of bioenergy in Nigeria, include poor waste management (poor collection efficiency, non-segregation of wastes, uncertainties in MSW generation data, poor funding), resource consideration (water supply, land availability), management of by-products (flue gas production, H_2S, etc.), poor comparative economic and market advantages of bioenergy production exacerbated by fossil fuel subsidies, technology and technical limitations and inconsistent policies [2]. These factors must be addressed to scale wide adoption of bioenergy in Nigeria. All these indicate the need for adequate investments in the infrastructure for MSW collection. It also supports a model shift away from waste disposal as a final solution to waste treatment for resource (energy and material) recovery. The revenues generated from the shift will not only self-finance waste management, as they will also create investments which anchor other value-added industries [22]. Though the estimation were summed for the whole 36 state capitals and the FCT Abuja, the energy recovery may not be carried out on a large scale or centralized facilities. It may be useful to initiate dispersed facilities at household, collection of households or neighborhood levels, depending on the business forms and logistic (collection) measures that are feasible. Going with centralized large-scale operations for each city, electricity production can be fed into the national grid or off-grid, depending on the WtE capacity generation and utilization.

For WtE plant, revenue sources are tipping fees, trading of generated heat, electricity and steam, and trading of other end-products, such as ash, etc. In developed countries, subsidies paid by the government are revenue sources for WtE plants. This is because WtE is viewed as a renewable source of energy. Tipping fees are very challenging in Nigeria. Most households don't pay the levies. In the US, the net cost per ton of MSW handled ranges from $36/ton to around $85/ton for city generation rate of 1500 tons/day and 400 tons/day, respectively [12]. The issues of establishing functional and effective logistic arrangements for proper management (collection, transport and pre-treatment) of MSW to support valorization is a concern [1,2,22]. Only 44% of the total MSW generated in Nigeria is collected. However, there is variation among the urban areas. Lagos, the most populous city in Nigeria, has a collection efficiency of 10%, while Ibadan (3rd most populated) has a collection efficiency of 40%. Conversely, the average efficiency for lower to middle income countries (LMICs) is 71% [29]. Further, waste segregation at source is very poor among Nigerians. In major cities in Nigeria, only 13% (Umuahia) [48] and 56% (Abeokuta) [49] of the households segregate their wastes. The poor practice is related to low-level of awareness, poor collection efficiency, perceived high cost of waste services and others [50]. Since the wastes are usually not collected, households see no reason to sort it since they will eventually dispose of it to the environment (water bodies, vacant plot, etc.) or burn them.

Accordingly, the data (or results) created by this work can offer useful material (potential energy production, revenue generation and GHGs abatement) to direct planning in this regard. The planning may include assessing the initial investment and operational outlays for the different valorization processes at various levels, along with the available demand for the recovered bioenergy to define those suitable for the different cities. The assessment is also important, considering the wide differences in socio-economic, technological, and investment environment across the different regions of the country. Considering the potential revenue generation from energy (and material) valorization from OFMSW and MSW in general, cities can enter into partnership or devise fiscally sustainable models to aid efficient waste collection. The different valorization methods also have distinct environmental issues [22]. Incineration could lead to ash production and air pollution, such as flue gas production, which includes SO_2 and dioxin, while AD produces hydrogen sulfide (H_2S) and CO_2 as some of the by-products. Landfill gas-to-energy could lead to methane leakages, meaning leaching of pollutants to groundwater if not properly engineered. However, there are existing treatments for the produced wastes. Also, emerging research is turning the by-products of the processes as feedstock for other applications. The ash from incineration is increasingly being coopted into cement production. The flues from incineration can be reduced by absorbents, such as lime and activated carbon. AD by-products can be treated via water and chemical washing, pressure swing adsorption (PSA) [2]. There is, therefore, need for involvement of different stakeholders to create favorable investment policies, which should include subsidies, tax rebate or other climate change incentivized funding.

5. Conclusions

Population increase, urbanization, economic growth and consumption is causing huge amount of MSW (and OFMSW) generation in cities across Nigeria. However, the wastes are not properly disposed, causing environmental pollution. Thus, there is a need for energy valorization to support proper waste management and provision of energy. Waste generation rate in the 36 states' capitals and the FCT, Abuja were identified. Apart from Ibadan, which has 0.31 kg/cap/day, the average generation rate of the other four most populous cities (Lagos, Kano, Benin City and Port Harcourt) is 0.65 kg/cap/day. This is higher than the average of 0.27 kg/cap/day for the other 32 cities. About 4.7 million TPY of OFMSW is generated in the 37 cities. Daily OFMSW generation ranges from 10416 TPY (Damaturu) to 1.6 million TPY in Lagos. About 1.82 billion Nm^3 of biogas could be recovered from AD of the OFMSW generated in the 37 cities each year; 984 Gg (1085688 tons) of CH_4 can be recovered from the landfill gas technology, while drying and densification will produce about 1.82 million tons of solid fuel. The energy potential of the different processes per ton of treated OFMSW shows the following: 0.211 MWh/ton (incineration), 0.43 MWh/ton (AD) and 0.55 MWh/ton (densified solid fuel). Energy production from OFMSW should be established as a crucial part of an integrated waste management strategy, while at the same time, producing energy. These will aid mitigate GHG emissions and support climate change policies. It should also be a part of the country's energy transition plant, supporting renewable energy mix.

6. Limitations of the study

The true measure of energy potential generation of OFMSW from the different methods depends on many factors. Since the paper adopted secondary data and mathematical formulas to make the estimation, this is accepted as a limitation to the paper. MSW segregation is very poor in Nigeria. The separation by municipal waste managers of WtE plants will certainly have a cost implication. This is a critical limitation to determining the true cost of OFMSW energy valorization for a country like Nigeria, where the practice of segregating waste is very poor.

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Conflict of interest

We declare no conflicts of interest in this paper.

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