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Research paper

Estimation of power generation from municipal solid wastes: A case Study of Ilorin metropolis, Nigeria

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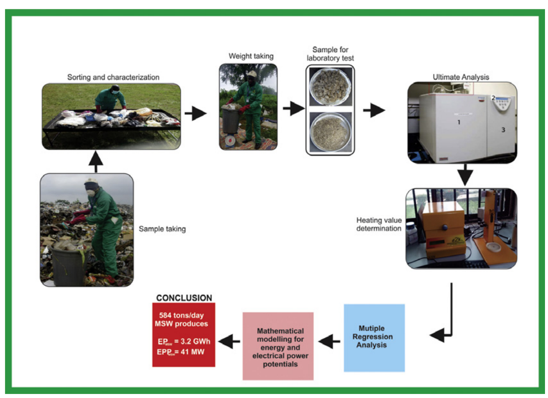
HIGHLIGHTS

- The possibility of waste to energy in Ilorin metropolis, Nigeria has been established.
- The study achieved maximum characterization of the various fractions of the wastes.
- The study established the heating values of the waste streams.
- The study established the energy potential (EP_{MSW}) of the MSW based on the energy content of 584 tons/day MSW.
- The Electrical Power (EPP_{MSW}) of about 40555 kW or 41 MW and Power to Grid of 27 MW was established.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, attempt was made to estimate the quantity of municipal solid waste (MSW) generated per annum, the generation rate in kg/capita/day as well as the quantity and the fractions of the waste streams available for energy production. The physical characterization of the waste streams into fractions was conducted. The proximate and ultimate analyses of the waste fractions were performed. Heating values of the waste streams was determined experimentally using a bomb calorimeter. It was concluded that 1% increase in carbon and sulphur will increase heating value by 79.08% and 10.83% respectively while 1% increase in hydrogen and nitrogen decrease heating value by 30.2% and 619.1% respectively. The energy potential (EP_{MSW}) of the MSW based on the energy content of 584 tons/day MSW, is about 3,244,444 kWh or 3,244 MWh, Electrical Power (EPP_{MSW}) of about 40555 kW or 41 MW and Power to Grid of 27 MW.

1. Introduction

Municipal solid waste (MSW) is the aggregate of the discarded unwanted materials, which are generated from the daily activities of man; as they interact with their environment. MSW are mostly wastes from residences, commercial centres and institutions. In most developing and developed nations of the world, increase in population, prosperity and urbanization has posed more challenges for municipalities in the management of MSW streams, especially in a changing climate (Ahmed, 2012). Municipal solid waste (MSW) generation rate has increased globally over the years; due to population growth, changes in lifestyle, technology development and increasing consumerism (Omari et al., 2014). It was reported that increase in MSW generation rate is because of the quest

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for modern urban life throughout the globe (Islam, 2016). The spiral increase in waste generation rate will lead to a rise in environmental challenges if not adequately managed (Johari et al., 2012). The global MSW data showed a generation rate of 0.68 billion tons per year in 2000 and 1.3 billion tons per year in 2010, while the projection for 2025 is at 2.2 billion tons per year and 4.2 billion tons by 2055 (Hoornweg and Bhada-Tata, 2012). MSW generation per capita is a core indicator of environmental pressure to evaluate the degree of generation for an effective MSW management planning. It is also used to compare MSW generation intensity between one nation and another. The generation rate in United Kingdom is reported to be 1.34 kg/capita/day, it is 2.13 kg/capita/day in United States, in South Africa, it is 2.00 kg/capita/day; 0.09 kg kg/capita/day in Ghana and 0.58 kg/capita/day in Nigeria (Kawai and Tasaki, 2016). The rates at which MSW are generated, is alarming and constitutes a great problem for the government to manage particularly in Ilorin; because, residues of the used products are mostly discarded indiscriminately (Ajadi and Tunde, 2010). The illegal and indiscriminate disposal of these waste components contributes greatly to air, water, and environmental pollution. Ilorin metropolis was selected for this study because of its demographic growth, urbanization, industrialization and influx of refugees from North Eastern part of Nigeria due to the activities of the armed insurgents (the bokoharams), over years now. Moreover, the city functions as the capital city of Kwara state as well as the headquarters for three local government areas (Ilorin East, Ilorin west and Ilorin South) which has resulted to the generation of a very high quantity of MSW in the metropolis. Despite the rise in MSW generation rate in Ilorin metropolis, the city still faces energy crisis that pose challenges to their economic and social development. Adopting an integrated MSW management method that encompasses thermal degradation and energy recovery, recycling and others will ensure adequate and efficient waste management system (Omari et al., 2014). Utilizing MSW as a renewable energy source for power generation, would complement the current inefficient grid power supply witnessed in the city. This will thereby boost the economy of the city and Kwara state by extension. According to Ogunjuyigbe et al. (2017), clean energy and green environment are very essential to the growth and living standard of every nation; hence effective management, recycling and energy recovery utilization of MSW (waste-to-energy) could provide a sustainable and environmental friendly solution to bridging the gap between energy and environmental development. Waste-to-energy (WTE) requires thermal and biological processes to extract useful energy that is stored in the combustible biogenic fractions of the MSW to produce heat (steam) or power (electricity) or both (combined heat and power). The average electrical energy and power rate in Nigeria is in the range of 107 kWh, 12 W per capita per annum. This is quite inadequate compared to what is obtainable in some other developing countries that include Malaysia (3310 kWh and 337 W) and South Africa (4347 kWh and 496 W) (Hoornweg and Bhada-Tata, 2012). In 2016, the MSW generated by the world city is about 2.01 billion tons; at a generation rate of about 0.74 kg/capita/day (World Bank). In 2005, about 262.4 million tons of MSW was generated at the rate of 4.48 pounds/capita/day in US (United States Environmental Protection Agency (EPA), 2017). In the metro cities of India, about 3 billion people is responsible for the generation of MSW at the rate of 1.2 kg/capita/day (Tahir et al., 2015). In East Asia and Pacific, 777 million people are responsible for waste generation, at the rate of 738,959 tons/day and 0.95 kg/capita/day. Latin America and Caribbean of about 400 million people generates 437545 tons of MSW in a day at the rate of 1.09 kg/capita/day; about 426 million people in South Asia, is responsible for 192411 tons of MSW in a day at the rate of 0.45 kg/capita/person. MSW generation data for region, in 2012 also stated that 261 million people is responsible for 169120 tons of MSW per day in Africa at the rate of 0.65 kg/capita/day (Wale, 2018).

In Nigeria about 196 million people produces 32 million tons of solid municipal waste annually, and only 20%–30% are collected. In the city of Onitsha, more than 730412 people generates 370706 tons/annum; and in Lagos, the commercial center of Nigeria, 21 million people produces more than 10,000 tons of MSW every day at the rate of 0.5 kg/capita/day (Maxwell, 2010). In 2004 the MSW generated in U.S.A was at the rate of 942 kg/capita/annum to produce 8461 GWh of electricity; U.K at the rate of 482 kg/capita/annum generates 1422 GWh of electricity of power; Switzerland with 730 kg/capita/annum produces 1102 GWh; India at rate of 385 kg/capita/annum generates 1090 GWh; Japan at generation rate of 624 kg/capita/annum produces 6574 GWh; Hungary at MSW generation rate of 388 kg/capita/annum produces 137 GWh of electricity; Canada at generation rate of 850 kg/capita/annum produces 89 GWh of electricity; France with rate of 511 kg/capita/annum produces electrical power of 1824 GWh (International Renewable Energy Agency (IRENA), 2018). The first major power plant in Africa, is in Ethiopia 110 MW, Ghana is proposing 60 MW Armech thermal power plan and South Africa has more than 6,327 MW (United Nations Environmental Programme (UNEP), 2017). If waste-to-energy project for power generation is encouraged in Nigeria, it will serve as an environmentally friendly and sustainable method to ameliorate waste management problems and insufficient supply of electricity. There are more than 800 thermal waste-to-energy plants in about 40 countries around the globe lately; they utilize about 11% of the MSW generated globally and produce about 429 TWh of power (Tan et al., 2005). Waste-to-energy practice in Nigeria is limited to traditional biomass (wood fuel and charcoal) to complement grid heating and cooking in the rural areas. In this study, the quantity of MSW generated per year and the MSW generated per capita per day in Ilorin metropolis of Kwara State of Nigeria was determined. The available combustible waste fractions that could be used for power generation per day and their heating values were determined as well as the proximate and ultimate analyses of the waste fractions. The capacity of the required steam power plant to convert the available combustible waste fractions energy to electricity was designed. Therefore, the aim of this research was to estimate the power generation capacity from municipal solid wastes in Ilorin metropolis, North-Central, Nigeria.

2. Materials and methods

2.1. The study area

Ilorin the capital city of Kwara State Nigeria, is located on latitude 8°30'N and longitude 4°35'E with an area of about 100 km^2 (Ajadi and Tunde, 2010). The city is made up of three Local Government Areas viz: Ilorin East, Ilorin West, and Ilorin South. The demographic growth of the city over the years is responsible for the continuous rise in MSW generation rate as well as its consequential effects. The National Population Commission (NPC), gives the population census of Ilorin metropolis in 2006 to be 781934 people: Ilorin East 207462, Ilorin South 209251 and Ilorin West 365221. The population projected for 2011 is 908490: Ilorin East 241040, Ilorin South 243120 and Ilorin West 424330. Ilorin is characterized of traditional town alongside a modern urban centre. The centre of the city encompasses the Emir's palace, the Central mosque and the Emir's market. The transitional zone contains deteriorating houses and the independent working man zone, which consists of second generative immigration into the city. The fourth zone is characterized of citizens that are in the categories of: middle class, businessmen and the professionals (Ajadi and Tunde, 2010). The commuter zone is the last; it consists of small towns villages and hamlets e.g. Tanke, Ganmo, Amoyo etc. The metropolis has above 120 roro-bins placed by Kwara State Environmental Protection Agency (KWEPA) spatially positioned at strategic locations of the city, for collection of MSW generated in different streets and public places. The map showing the distribution of rolling waste-containers (Roro – bins) into which people deposit their wastes in their streets (at collection centres) before they are lifted by arm roller equipment to the dumpsite is shown in Fig. 1. The metropolis has some designated locations for dump sites which include: Airport road dump site (about 5 hectares), Lasoju (Eyenkorin) dump site along Ilorin-Ogbomosho express road (about 8 hectares), Oko-Olowo dumpsite along Alapa (20 hectares) and Asa – dam road dump site behind Dangote mill. As at the time of this study, only Lasoju (Eyenkorin) dump site was functional, and the available space was already exhausted with heaps of MSW dumped by the collection trucks.

2.2. Prediction of the population responsible for waste generation in Ilorin Metropolis as at the period of the study

The population data collected form National Population Commission (NPC), gives the population census of Ilorin metropolis for 2006 and the projected population for 2011. The population responsible for waste generation in 2016, was predicted using a modified Malthusian model equation (Mehmet, 2013), in Eqs. (1) and (2).

$$P_t = P_{(t-1)} * e^{k_p t} \quad (1)$$

Where, t is the time of interest in year, P_t is the estimated population at year t, $P_{(t-1)}$ is the population at the previous year of concern, and K_P is the annual population growth rate constant.

The annual population growth rate,

$$K_P = \left[\frac{p_{pr}}{p_p}\right]^{1/n} - 1 \quad (2)$$

where p_{p_r} is the present population, p_p is the past population and 'n' is the number of years involved.

2.3. Prediction of the quantity of MSW generated in Ilorin Metropolis per day

The amount of MSW generated annually in any metropolis, is of fundamental importance in MSWM decisions and should be reliable because of the budgets prepared per annum by the municipalities for waste management based on annual MSW generation (Kawai and Tasaki, 2016). The MSW generated can be predicted (where there is no weighbridge) using the mathematical model in Eq. (3); (Kosuke and Tomohiro, 2016). This was estimated based on the available information on the facts and figures on collection and transportation of waste.

$$MSW_{gen.} = \sum_{j=1}^{365} \sum_{i=1}^{m} (C_i \times V_i \times d_i \times t_{ij}) \quad (3)$$

Where m is total number of trucks, C_i is the capacity of truck i (m^3/truck), V_i is the loading volume ratio of truck i, d_i is the density of MSW loaded on truck i (tons /m^3), and t_{ij} is the number of trips by truck i on day j (frequency of trips/day).

2.4. Characteristics of municipal solid waste data

The samples characterized in this study were taken from Lasoju/Eyenkorin dumpsite. European commission for solid waste analysis tool (European Commission Solid Waste Tool (ECSWA-Tool), 2004); recommended 30 samples as being appropriate for this kind of study. Nevertheless, samples were taken twice per week (Tuesday and Saturday) for eight months; making 62 samples altogether, to avoid eventual error that may occur due to insufficient samples. A specific bin volume of 240 litres is considered in each sample as suggested by EC SWA-Tool (European Commission Solid Waste Tool (ECSWA-Tool), 2004); and each is weighed and hand sorted into different components in screening equipment, 1.5 m × 3 m with 10 mm × 10 mm mesh surface size designed for heterogeneous solid waste recommended by World Health Organization (WHO) and adopted by Issam et al. (2010). In the entire period of characterization, the waste streams were sorted into nineteen waste fractions; the waste stream distribution in the city is represented in Table 4. Nine waste components out of the nineteen waste fractions characterized, were considered for energy content analyses; because of their regular occurrence in the wastes streams and combustibility. They include food residue, paper, plastic bottles, textiles (rag), wood, grass/garden trimmings, nylon, packaging box (carton) and polythene-sac shown in Table 5.

2.5. Elemental analysis

The percentage chemical elements in the MSW fractions (carbon (C), hydrogen (H), nitrogen (N), Sulphur (S), oxygen (O)) were determined using Flash EA 1112 Elemental analyzer; based on the standard ASTM D5291 (Titiladunayo et al., 2018). Dried and powdered sample of about 0.5 g was weighed into a crucible and combusted. The flue was passed into a chromatography column. The oxides of nitrogen, sulphur, hydrogen and carbon produced were detected by the thermal conductivity detector (TCD), and the electrical signal produced was processed by 'Eager 300 software' to give percentages of nitrogen, carbon, hydrogen, and sulphur contained in the sample. The samples were replicated three times in the experiment, and the average values of the results considered as the typical values in Table 6.

2.6. Determination of the heating value of the waste components

The determination of high heating value (HHV) or high calorific value (HCV) of MSW is important for the efficient design and operation of waste-to-energy conversion-based technologies. The HHV was determined by using a bomb calorimeter (*e 2k* combustion Calorimeter), based on standard ASTM D5468-02 (Shi et al., 2016). 0.5 g weighed component sample was burnt in a high-pressure oxygen atmosphere, in the cylindrical vessel called a bomb. The vessel was later placed at the filling station and filled with oxygen to the pressure of about 2000 MPa; then the mass of the test sample (0.5 g) was inputted to the system through the computer connected to it. The equipment prompted that the bomb be put into the calorimeter. After placing the vessel in the Calorimeter, the door was closed for the analysis to begin. The result was later displayed on the screen after completion to give the HHV of each component. The low heating value or net calorific value (i.e. high heating value less heat of vaporization of water content), is the heating value required in calculating the energy potential of the municipal solid waste (Mehmet, 2013). The low heating value, LHV^1 of each component presented in Table 7, was calculated using HHV obtained from calorimeter, in Eq. (4) (Islam, 2016; Kumar et al., 2010; Ibikunle et al., 2018).

$$LHV^1 = \sum_{1}^{9} W_j \times HHV_j \quad (4)$$

Where LHV^1 is the lower heating value, HHV_j typical heating values of MSW component-j (net heating value obtained from bomb calorimeter) and W_j is the weight fraction (%) of component-j (Islam, 2016).

The low heating value, LHV^2 presented in Table 8, was calculated by adopting Dulong's model in Eq. (5), using the chemical

Table 1
Demographic data of Ilorin metropolis.

Year	Demographic centers of Ilorin metropolis	Population	Total	Source
2006	Ilorin East	207,462	781,934	NPC (2006)
	Ilorin West	365,221		
	Ilorin South	209,251		
2011Projection	Ilorin East	241,040	908,490	NPC (2006)
	Ilorin West	424,330		
	Ilorin South	243,120		
2016Prediction	Ilorin East	280,049	1,055515	Mehmet (2013) (1) and (2)
	Ilorin West	493,001		
	Ilorin South	282,465		
2017Prediction	Ilorin East	288,578	1,087,660	Mehmet (2013) (1) and (2)
	Ilorin West	508,015		
	Ilorin South	291,067		

Table 2
The MSW collection vehicles in Ilorin metropolis.

S/N	Types of vehicle	Quantity provided	Number functional	Capacity/ vehicle (kg)	Volume/ vehicle, Vv (m^3)	Number of/ trips/vehicle/ day, Tn
1	Dino Tipper Truck	10	5	20,000	16	3
2	Hino Tipper Truck	5	3	25,000	22	3
3	Scania Compactor	10	2	30,000	22	2
4	Arm Roller	5	3	15,000	8	5
	Total	30	13	90,000	68	13

Table 3
Estimation of MSW generated in Ilorin/year based on transportation facts.

S/N	Types of Vehicle	Number of trucks/day, *l*	Capacity/ vehicle (tons)	Volume/ vehicle, *C* (m3)	Avg. volume ratio of a truck	Density of MSW loaded on truck, *d* (tons/m3)	Number of Trips/vehicle/ day, *t*	MSW generated (tons/yr)	MSW generated (tons/day)
1	Dino Tipper Truck	5	20	16	0.95	1.25	3	104025	285
2	Hino Tipper Truck	3	25	22	0.95	1.136	3	78019	214
3	Scania Compactor	2	30	22	0.95	1.364	2	41610	114
4	Arm Roller	3	15	8	0.95	1.875	5	78019	214
	Total	13	90	68	3.8	5.625	13	301673	827

Table 4
The combined Physical Characterization of the MSW steams for Eight months.

Types	Months								Mean	Total Wt (kg)	Wt (%)	Volume (m^3)	kg/cap/ day
	1 NOV. Wt (kg)	2 DEC. Wt (kg)	3 JAN. Wt (kg)	4 FEB. Wt (kg)	5 MAY Wt (kg)	6 JUN. Wt (kg)	7 JUL. Wt (kg)	8 AUG. Wt (kg)					
Food residue	3.70	46.3	10.9	8.0	28.2	56.5	55.1	109.8	$39.8 \pm 35.$	318.5	10.37	1.43	0.081
Wood	1.60	3.4	4.0	0.00	4.70	2.40	8.00	0.60	3.1 ± 2.56	24.7	0.80	0.11	0.006
Paper	14.8	31.5	30.5	12.6	21.5	15.5	32.5	26.80	23.2 ± 8.1	185.70	6.04	0.93	0.047
Carton	10.4	49.6	12.5	7.80	56.8	47.5	50.0	63.00	37.2 ± 23	297.60	9.69	1.38	0.076
Texiles (rag)	27.2	46.0	42.4	27.3	21.6	27.4	21.5	60.40	$34.2 \pm 13.$	273.80	8.91	1.42	0.070
Toiletries	18.4	14.1	29.1	31.1	33.7	22.8	25.6	15.60	23.8 ± 7.3	190.40	6.20	1.06	0.049
Feaces	1.40	11.6	1.00	5.10	6.50	14.6	4.60	3.60	6.1 ± 4.78	48.40	1.58	0.24	0.012
Cow dung	8.70	3.0	3.20	0.00	5.90	13.4	6.60	1.80	5.3 ± 4.29	42.60	1.39	0.21	0.011
Nylon	59.0	70.4	72.2	52.5	58.4	66.8	41.1	47.40	$58.5 \pm 11.$	467.80	15.23	2.48	0.119
Polybag	23.2	11.3	24.2	8.20	19.8	17.5	25.92	33.40	20.4 ± 8.1	163.52	5.32	0.84	0.042
Plastic bottle	7.00	64.2	18.4	18.30	80.5	48.4	26.5	37.40	$37.6 \pm 25.$	300.70	9.79	1.42	0.077
Rubber	0.40	0.1	1.20	0.00	0.80	1.00	0.80	1.00	0.6 ± 0.44	5.30	0.17	0.01	0.001
Leather	0.60	0.2	0.00	0.00	0.00	1.00	0.00	0.40	0.2 ± 0.36	2.20	0.07	0.00	0.001
Ceramics	10.4	9.8	20.4	6.00	7.90	9.60	9.60	8.60	10.3 ± 4.3	82.30	2.68	0.44	0.021
Bones	2.60	0.0	0.80	2.50	7.60	8.60	3.20	2.20	3.4 ± 3.06	27.50	0.90	0.14	0.007
Tins/Metals	8.00	35.0	8.00	4.20	45.2	15.2	22.1	6.80	$18.1 \pm 14.$	144.50	4.70	0.67	0.037
Sand/Ash	11.9	9.3	15.30	9.30	12.45	14.60	11.20	6.40	11.3 ± 2.9	90.45	2.94	0.48	0.023
Others	20.00	50.6	59.40	26.80	29.30	37.50	25.00	20.40	$33.6 \pm 14.$	269.00	8.76	1.40	0.069
Grand Total	260.9	464.6	360.40	222.10	459.05	444.54	404.62	456.00		3072.21	100.00	15.37	0.784

properties obtained from ultimate analysis (Vairam and Ramesh, 2013)

$$LHV^2 = 81C + 342.5\left(H - \frac{O}{8}\right) + 22.5S - 6(W + 9H) \qquad (5)$$

Also, the low heating value, LHV^3in Table 8, was determined using ultimate values by adopting Steuer's model in Eq. (6) (Ogwueleka and Ogwueleka, 2010)

$$LHV^3 = 81\left(C - \frac{3}{8}O\right) + 57\frac{3}{8}O + 345\left(H - \frac{O}{16}\right) + 25S - 6(W + 9H)$$

Table 5
The waste components considered for Energy Generation.

MSW fractions	Months										MSW/day (tons)
	1	2	3	4	5	6	7	8			
	NOV. Wt (kg)	DEC. Wt (kg)	JAN. Wt (kg)	FEB. Wt (kg)	MAY Wt (kg)	JUN. Wt (kg)	JUL. Wt (kg)	AUG. Wt (kg)	TOTL Wt. (kg)	Wt. %	
Food residue	3.7	46.3	10.9	8.00	28.2	56.5	55.1	109.8	318.5	10.4	85.75
Wood	1.6	3.4	4.0	0.00	4.7	2.4	8.0	0.6	24.7	0.8	6.62
Paper	14.8	31.5	30.5	12.6	21.5	15.5	32.5	26.8	185.7	6.0	49.95
packaging box	10.4	49.6	12.5	7.80	56.8	47.5	50.0	63.0	297.6	9.7	80.14
Grass/trimmings	31.6	8.2	6.9	2.40	18.2	24.2	35.3	10.4	137.2	4.5	36.97
Texiles (rag)	27.2	46.0	42.4	27.3	21.6	27.4	21.5	60.4	273.8	8.9	73.69
Nylon	59.0	70.4	72.2	52.5	58.4	66.8	41.1	47.4	467.8	15.2	125.95
poly-sac	23.2	11.3	24.2	8.20	19.8	17.5	25.9	33.4	163.5	5.3	43.99
Plastic bottle	7.0	64.2	18.4	18.30	80.5	48.4	26.5	37.4	300.7	9.8	80.96
Grand Total	179	331	222	137	310	306	296	389	2170	71	584

Table 6
The result of ultimate analysis of the waste sample.

MSW Fractions	C %	H %	N %	S %	O %	HV %
Food residue	38.020 ± 0.44	0.165±0.00	4.938±0.05	3.100 ± 0.02	0.081 ± 0.00	18.624
Wood	36.523 ± 0.62	0.105±0.02	4.501 ± 0.04	0.101 ± 0.02	0.067±0.00	18.418
Paper	35.327±0.08	0.107±0.02	4.748±0.24	0.081 ± 0.00	0.069±0.00	17.038
Packaging box	20.987±0.06	0.111 ± 0.00	2.765±0.10	0.078 ± 0.03	0.082 ± 0.00	15.883
Grass/Trimmings	30.860 ± 0.11	0.098 ± 0.02	3.862 ± 0.06	0.071 ± 0.00	0.064 ± 0.00	17.838
Textiles (rag)	34.047±0.14	0.098 ± 0.00	4.373 ± 0.00	0.084 ± 0.00	0.075 ± 0.00	15.747
Nylon	22.057±0.08	0.110 ± 0.00	2.823±0.02	0.052 ± 0.00	0.076±0.00	46.160
Poly sac	20.950±0.11	0.111 ± 0.02	2.669±0.01	0.052 ± 0.00	0.078±0.00	39.352
Plastic bottle	23.050±0.03	0.105±0.00	2.925 ± 0.00	0.078±0.02	0.078±0.02	37.282

Table 7
The heating value analysis of MSW components using Calorimeter.

Types	HHV(MJ/kg)	Mean	Wt. %	LHV[1] = HHV*Wt.%
Food residue	18.624	18.624 ± 0.545	10.37	1.9313
Wood	18.418	18.418 ± 0.026	0.8	0.1473
Paper	17.038	17.038 ± 0.920	6.04	1.0291
packaging box	15.883	15.883 ± 1.208	9.69	1.5391
Grass/trimmings	17.838	17.838 ± 0.251	4.47	0.7974
Texiles (rag)	15.747	15.747 ± 2.834	8.91	1.4031
Nylon	46.160	46.160 ± 0.246	15.23	7.0302
Polythene sac	39.352	39.352 ± 0.659	5.32	2.0935
Plastic bottle	37.282	37.282 ± 0.734	9.79	3.6499
Total	226.324		70.62	19.6

Table 8
The heating value analysis of MSW components using Dulong[2] and Steuer[3] models.

Types	C %	H %	N %	S %	O%	M%	LHV[2]	LHV[3]
Food residue	0.381	0.001	0.049	0.031	0.001	0.060	**28.10**	**27.45**
Wood	0.357	0.001	0.045	0.001	0.001	0.130	**27.01**	**26.42**
Paper	0.354	0.001	0.044	0.001	0.001	0.070	**27.10**	**27.21**
packaging box	0.211	0.001	0.027	0.001	0.001	0.040	**16.00**	**16.02**
Grass/Trimmings	0.307	0.001	0.039	0.001	0.001	0.100	**22.45**	**22.51**
6Texiles (rag)	0.342	0.001	0.044	0.001	0.001	0.060	**27.12**	**27.34**
Water-Nylon	0.221	0.001	0.028	0.001	0.001	0.000	**18.00**	**18.10**
Polythene-sac	0.210	0.001	0.027	0.000	0.001	0.000	**17.12**	**17.01**
Plastic bottle	0.230	0.001	0.029	0.001	0.001	0.000	**18.10**	**17.92**
Total	**2.613**	**0.009**	**0.333**	**0.036**	**0.007**	**0.460**	**201.00**	**199.98**
Average	**0.037**	**0.001**	**0.037**	**0.004**	**0.001**	**0.051**	**22.33**	**22.21**

(6)

2.7. Multiple regression analysis

Multiple regression analysis was used to model the energy content of the municipal solid waste (MSW) using GRETL statistical software (Ibikunle et al., 2018). The multiple regression on high heating value of the MSW was estimated based on the chemical elements in the MSW fractions. Diagnostic check was performed by using Jarque–Bera test to determine the error distribution. The correlation of the regressors were examined by using variance inflation factor (VIF) for a diagnostic check of a problem of multicollinearity. The regression model for the ultimate analysis is expressed in Eq. (7):

$$H\hat{V} = 1.3849 + 85.0807\hat{C} - 28.9675\hat{H} - 666.125\hat{N} + 11.6296\hat{S} \quad (7)$$

where: HV is the heating value, C is the carbon percentage content of the municipal solid waste, H is the hydrogen content percentage, N is the nitrogen percentage content and S is the Sulphur percentage content.

Table 9
Multiple regression on Chemical Elements using OLS.

Ordinary Least Square Estimator and its Diagnostic check					Ridge Regression	
Regressors	Coefficient	Standard error	t-ratio	*p*-value	Regressors	Coefficient
constant	1.3849	9.46871	0.1463	0.89079	constant	1.53324
C__	85.0807	23.2496	3.6594	0.02159	C__	79.08237
H__	−28.9675	71.9485	−0.4026	0.70782	H__	−30.16026
N__	−666.125	182.261	−3.6548	0.02168	N__	−619.09869
S__	11.6296	3.60443	3.2265	0.03208	S__	10.83630
R-squared	0.837249	Ftest	5.144354**			
Adjusted R-squared	0.674498	Jarque–Bera test	0.471254 (0.790075)			
MAX(VIF)	161359.816					

***, ** and * denote significant levels at 1%, 5% and 10% respectively. Value in parenthesis is the *p*-value.

Table 10
The estimated energy and electrical potentials of the MSW.

1	W_{MSW} (tons/day)	LHV (MJ/kg)	EP_{MSW} (MWh)	EPP_{MSW} (MW)	GP (MW)
	584	20	3244	41	27
2	Conversion ratio 1000 kg = 1 ton	10^6 J = 1 MJ	1 kWh = 3.6 MJ	$\eta = 30\%$	η_g = 90%, and $\eta_p = 75\%$

2.8. Estimation of the electrical power generation from municipal solid waste

2.8.1. Estimation of energy potentials of the msw (EP_{msw})

From the MSW generation prediction, in Table 3, about 827 tons of MSW is predicted per day and about 70% of the predicted quantity of waste is considered for energy generation i.e. 584 tons/day as presented in Table 5. The net low heating value (LHV_{msw}) considered for energy production is 21 MJ/kg which is the average heating value obtained from (LHV^1, LHV^2 and LHV^3) in Tables 7 and 8.

According to Kumar et al. (2010); Ibikunle et al. (2018), Gupta (2013) and Daura (2016), energy potential recovery from MSW (EP_{msw}) is calculated in Eq. (8):

$$EP_{msw} = LHV_{msw} \times w_{msw} \times \frac{1000}{3.6} \tag{8}$$

Where EP_{msw} is the energy potential from MSW, W_{msw} (tons) is the weight of MSW, LHV_{msw} is the net low heating value of the MSW (MJ/kg). Converting ratio (1 kWh = 3.6 MJ).

The energy potential was also calculated applying Dulong's and Steuer's models in Eqs. (9) and (10) (see Table 9). respectively

$$EP_{msw} = \left[81C + 342.5\left(H - \frac{O}{8}\right) + 22.5S - 6(W + 9H)\right] \times w_{msw} \times \frac{1000}{3.6} \tag{9}$$

$$EP_{msw} = \left[81\left(C - \frac{3}{8}O\right) + 57\frac{3}{8}O + 345\left(H - \frac{O}{16}\right) + 25S - 6\,(W + 9H)\right] \times w_{msw} \times 277. \tag{10}$$

Where C is the wt.% of carbon content, H is the wt.% of hydrogen content, S is the wt.% of Sulphur content, W is the wt.% of moisture content and O is the wt.% of oxygen content. The average energy potential (EP_{msw}) obtained from Eqs. (8)–(10) is considered as the energy potential of the MSW streams of the metropolis, presented in Table 10.

2.8.2. Estimation of electrical power potential of the MSW (EPP_{msw})

Electrical Power Potential (EPP_{msw}) is calculated by using Eq. (11) (Kumar et al., 2010; Ibikunle et al., 2018; Gupta, 2013; Daura, 2016):

$$EPP_{msw} = 277.8 \times LHV_{msw} \times \frac{w_{msw}}{24} \times \eta \tag{11}$$

Where EPP_{msw} is the electrical power potential (kW), w_{msw}(tons) is the weight of MSW, LHV_{msw} is the net low heating value of the MSW (MJ/kg) and η is the conversion efficiency (20%–40%.) in a power plant (Klein et al., 2003; Muhammad et al., 2014) the conversion efficiency. The conversion efficiency of 30% is adopted.

Power to grid is obtained using Eq. (12).

Power to grid

$$GP = EPP_{msw} \times \eta_g \times \eta_P \times \frac{1}{1000}(MW). \tag{12}$$

Where η_g is the generator efficiency (assumed to be 90 %), η_p is the transmission efficiency (assumed to be 75 % of turbine work (W_T) Generator efficiency range is 85%–90% and turbine efficiency is 75%–80% (Bright Hub Engineering (BHE)).

3. Results and discussion

In this section, the summary of the quantity of MSW generated, the generation rate (kg/capita/day), the amount of MSW available for power generation in a day, the physicochemical and thermochemical characteristics of the MSW generated are presented. Regression model was fitted to variables derived from the ultimate analysis to show the correlation between the heating value and the constituent elements of the MSW; to ascertain how each independent variable affect the intensity of the net heating value of the wastes streams.

3.1. The predicted population

Based on the demographic data of 2006 census and the projected population for 2011 collected form National Population Commission (NPC), the population distribution for waste generation in the city for 2016, was predicted to be 1,055515 as shown in Table 1. The population responsible for the waste generation in Ilorin metropolis is about 0.54% of the population of Nigeria. The population density is used to determine the MSW generation rate of the city, to ascertain the reliability and sustainability of the MSW streams of the city as solid fuel for electricity generation.

3.2. Estimation of MSW generation

The collection Trucks/Equipment made available for the MSW management system in Ilorin metropolis is given in Table 2. It is only 43% of the collection vehicles provided, that are available (functional) for MSW collection, are: 5 Dino Tipper Trucks, 3 Hino

Tipper Trucks, 2 Scania compactors and 3 Arm roller plant. This is an evidence that the waste collection system in Ilorin metropolis lack enough equipment thereby necessitating insufficient collection. The MSW generated in the year 2016, is predicted to be 301672.5 tons/year and about 827 tons/day as presented in Table 3. The density of the MSW generated is 5.625 tons/m^3 and the generating rate, 0.78 kg/cap/day presented in Table 4. The combustible waste fractions available for energy generation per day is 584 tons of MSW as indicated in Table 5. In 2016, USA with MSW generation rate of 2.5 kg/capita/day, generates 8461 GWh of electricity (International Renewable Energy Agency (IRENA), 2018). This implies that Ilorin metropolis with MSW generation rate of 0.78 kg/capita/day has tendency of producing 2639 GWh of electricity via waste-to-energy technology. This implies, the more the amount of MSW fractions generated, the greater the expected power generation via waste-to-energy. The MSW collection rate can be improved on, by employing more operators in waste collection section and as well acquire more efficient collection equipment.

3.3. Physical characterization of MSW for Ilorin metropolis

In the characterization of the MSW for eight months shown in Table 4, the total weight of MSW components analysed was 3072.21.kg with specific volume of 15.37 m^3 and generation rate of 0.784 kg/cap/day. The components distribution in Fig. 2, shows Nylon waste as the highest waste fraction of 15.23%, Food residue 10.37%, followed by plastic bottle 9.79% and the least is Leather 0.07%. The first three waste components on the high side, are from food and drinks that common men can afford. This is an indication that majority of the populace of the city are low income earners. The generation rate of 0.784 kg/capita/day in Ilorin in 2016 compared 0.584 kg/capita/day of the entire nation (Kawai and Tasaki, 2016). The components of the waste stream considered for energy estimation and their corresponding percentage in the total waste generated and the fraction predicted per day is given in Table 5. About 71% of the MSW predicted is available for energy generation via combustion; this indicates that MSW streams of the metropolis is sufficient for energy production.

3.4. Elemental analysis

The ultimate analysis in Table 3 shows that the carbon range of the components analysed is 21%–38% with dispersion of 0.04 %–0.85%; the highest is food residue 38.08%, followed by wood 37.45% and polythene 21.07%. Hydrogen range is 0.09 %-0.17% with standard deviation of 0.001%–0.031%; the highest is food residue 0.17%, Polythene bagco-sac is 0.15% and the least is Textile (rag) 0.09%. Nitrogen range is 2.12%–5.10% with dispersion of 0.01%–0.71%; the highest is paper 5.10% followed by food residue 5.01% and the least is Polythene bagco-sac 2.12%. Oxygen range is 0.065%-0.085 with dispersion of 0.0006%–0.001%; the highest is nylon 0.085%, followed by packaging box (carton) 0.083% and grass/trimmings 0.065%. Sulphur range is 0.05%–3.13%. With dispersion of 0.002%–0.039%; the highest is food residue 3.13%, followed by wood 0.13% and the least is nylon 0.52%. The small amount of Nitrogen and Sulphur present, will ensure reduction of emissions during combustion. The high amount of carbon is an indication of sufficient heating value for energy generation (Vairam and Ramesh, 2013).

3.5. The results of heating value analysis

The three models in Eq. (4), 5 and 6 were used in analysing the heating value of the MSW, and give 19.5 MJ/kg, 22.3 MJ/kg and 22.2 MJ/kg respectively. Eq. (4), is the model used to estimate the low heating value (LHV^1) presented in Table 7, based on laboratory analysis performed by using bomb calorimeter. Eq. (5), is Dulong's model used to estimate the low heating value (LHV^2) based on ultimate analysis and Equation 6, is Steuer's model used to estimate the low heating value (LHV^3) based on ultimate analysis presented in Table 8. The average low heating value of 21 MJ/kg, is considered for electrical power production. This is about 44% of the energy in petrol, 46% of that of diesel, 49% of that of natural gas and 38% of that of methane and about 100% of that of biomass (World Nuclear Association (WNA)). Nylon is the waste component that has the highest heating value of 20.4%, Polythene bagco-sac 17.4%, Plastic 16.5% and the least is Textile (rag) 6.9%. The chart showing the relationship between the heating values of the municipal solid waste and the values from the ultimate analysis is presented in Fig. 3. The chart shows that the waste fractions with high carbon and Sulphur contents consequently have high heating value that will increase the rate of electricity generation while the fractions with high nitrogen content, have low heating value which will reduce the rate of electricity generation. The heating value analysis shows that, the higher the heating value of MSW the greater the expected energy generation.

3.6. Multiple regression analysis result

3.6.1. Ultimate analysis model

The result of multiple regression model developed, reveals the correlation between the net heating value of the MSW and the chemical elements obtained from ultimate analysis parameters (i.e. C, H, N, and S) is given in Table 6. The results of multiple regression analysis presented in Table 10 was obtained by using ordinary least square (OLS) estimator and ridge regression estimator. Jarque–Bera test used for diagnostic check, shows that the error term is normally distributed since the p-value, 0.79 is greater than 5% level of significance. The variance inflation factor (VIF) is another diagnostic check conducted to examine if the regressors are correlated (to ascertain if the tendency of multicollinearity). The rule of thumb says if the VIF is greater than 10 then there is multicollinearity which implies that the regressors are correlated. The problem of multicollinearity was corrected by adopting Ridge regression as an alternative method to OLS to correctly estimate the regression model. From the ridge regression estimate, carbon and Sulphur both have a positive effect on heating value (i.e. they contribute to higher electricity generation) while hydrogen and nitrogen have a negative effect (i.e. they cause reduction in electricity generation). About 1% increase in carbon and nitrogen will increase heating value by 79.08% and 10.83% respectively while a 1% increase in hydrogen and nitrogen decrease heating value by 30.2% and 619.1% respectively. The R-squared shows about 84% variation in the response expressed by the regressors. The F test shows that the overall model fitted to the data is significant at 5%.

3.7. Estimated electrical power generation from MSW

The estimated Energy Potential (EP_{MSW}) and Electrical Power (EPP_{MSW}) when MSW of about 584 tons is utilized for energy generation in a day is given in Table 10. The energy potential of the MSW (3244 MW), is the equivalent of 612 tons of dry wood, 401 tons of coal, 97 tons of hydrogen, 0.15 kg of $Uranium_{235}$, 357,000 litres of petrol and 324,000 litres of diesel (Deep Resource World press (DRW)). According to Ibadan Electricity Distribution Company (Ibadan Electricity Distribution Company (IBEDC), 2016), Kwara state needs 270 MW for 24 h stable supply of electricity. This implies, that waste-to-energy (WTE) using Ilorin MSW, will provide 15% of power demand in Kwara state. Also, it will help Nigeria Renewable Master Plan (REMP) achieve 10% of their goal for 2025 (IEA Nigeria Renewal Energy Master Plan, 2011). A decision support system that could determine the capacities of the

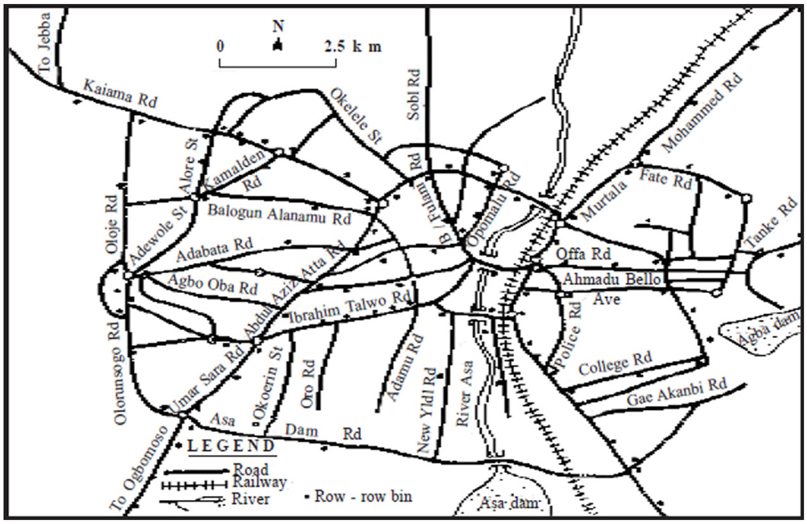

Fig. 1. Map of Ilorin Metropolis showing locations of Dumpsters (Row-row bins).
Source: Ministry of Lands and Surveys, Ilorin (Ajadi and Tunde, 2010).

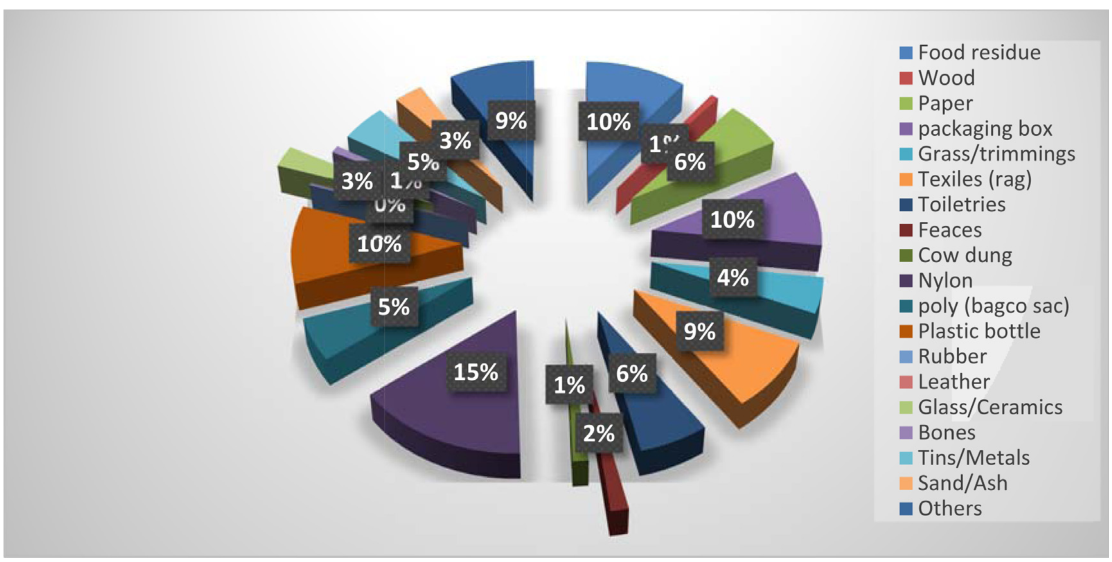

Fig. 2. Msw distribution for bright months.

power plant equipment, required to utilize the available MSW for electricity generation has given the capacities of equipment involved as follows: boiler 101 MW, turbine 41 MW condenser 60 MW. The MSW (fuel) consumption rate is 6.25 kg/s, steam consumption rate is 28 kg/s and the specific steam consumption rate is 2.48 kg/kW h. The power to grid produced is 27 MW. The performance of the software developed has been evaluated to be exact with the design calculations engaged in the design of the power plant capacity with above 98% efficiency.

4. Conclusion

The quantity of MSW predicted is about 320,000 tons/year, about 827 tons/day. The quantity useful for energy generation was about 584 tons/day and the generating rate was 0.78 kg/capita/day. The methodology and the number of samples taken at the dump site for the characterization in this study is quite enough, thereby preventing errors due to insufficient samples. It is concluded that 584 tons of combustible municipal solid waste in Ilorin with 21 MJ/kg heating value has the capacity to produce 3.2 GWh of energy potential, 41 MW of electrical power and 27 MW of power to grid.

5. Recommendation

The waste-to-energy technology recommended for Ilorin metropolis, is electrical energy generation from municipal solid waste (MSW) using Incineration Technology, because the combustible fraction of the wastes available for energy production is about 71% of the wastes streams. This will efficiently satisfy the power requirement in Ilorin metropolis, and about 15% of power demand in Kwara state (270 MW) for 24 h stable supply of electricity. The MSW fractions should be pretreated before they are used for energy production. to reduce the effect of moisture content, hydrogen and nitrogen constituents, that could reduce the efficiency of the heating value. The constituents of the flue gas produced during incineration process (which include Sulphur (IV) oxide (SO_2) and dioxin), can be reduced through absorbents like lime and activated carbon, and the byproduct can be gathered in a particle filter.

To have a sufficient and efficient waste collection, the collection routes must be properly planned to minimize distances covered by each truck between collection centres and disposal sites; this will ensure speed up collection and labour efficiency. Collection trips

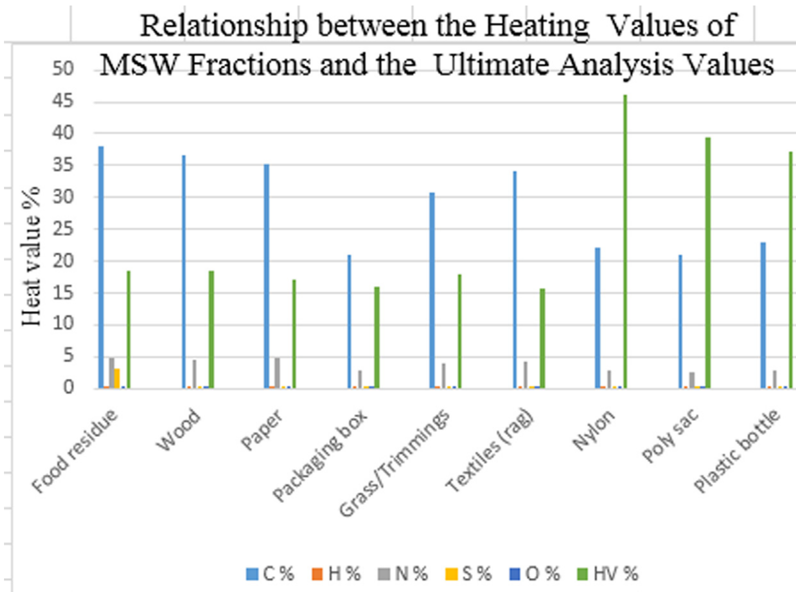

Fig. 3. The heating values versus the ultimate analysis of the MSW.

should be scheduled either for early morning or late at night to avoid running into traffic congestion. Communication crew should be established in the waste management system, to always give useful information concerning situations on the collection routes and centres as well as provide timely information for maintenance section about a breakdown vehicle during collection trip. The maintenance section should always perform optimum equipment life services to prevent downtime and ensure maximum capacity operation. The municipalities should also solicit for the input of NGOs and stakeholders of the community to ensure sustainable and efficient waste management programme.

The municipalities should be more committed to ensuring sufficient and efficient MSW management even financially by increasing the budget for waste management, training the required personnel for collection and processing sections and provide modern equipment that include crane-tipper loading system, pay-loader tipper system and compactor with bin-lift device for waste collection and disposal procedures.

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Conflict of interest

Authors declare no conflict of interest whatsoever.

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