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REGIONAL CASE STUDY

Exploration and prediction of wet season municipal solid waste for power generation in Ilorin metropolis, Nigeria

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Abstract

The wet season municipal solid waste (MSW) was characterized on Lasoju/Eyenkorin dumpsite for May to August 2020. The aggregate of waste generated was estimated to be 135,882 tons, while the aggregate characterized was estimated to be 80,700 tons. There are thirty-two samples of 240 L (bin of MSW) per sample considered in this investigation. There are twenty-one waste components categorized altogether, with packaging box having the highest proportion of 10.04%, followed by food residue of 9.64%, nylon 9.51%, and leather with the least fraction (0.75%) of the weight basis. Experimental investigations were performed on fourteen combustible fractions of the waste to determine the moisture content, elemental contents, and high heating value. The laboratory analysis reveals that the average carbon content available is 55%, 7% hydrogen, 1.35% nitrogen, 0.44% sulphur, and 30% oxygen; the low heating value of the waste was determined to be 23 MJ/kg. About 672 tons of MSW were investigated for energy production to give an energy and power potentials of 4.2 GWh and 53 MW discretely. The estimated electrical power potential for the wet season MSW is capable of meeting about 59% of the power demand for the Ilorin metropolis.

Keywords Municipal solid waste · Seasonal characterization · Combustible fractions · Heating value · Electrical power potential

Abbreviations

MSW	Municipal solid waste
WTE	Waste-to-energy
REMP	Renewable energy master plan
GHGs	Greenhouse gases
KWEPA	Kwara environmental protection agency
NPC	National population commission
ASTM	American Society for Testing and Materials
HDP	High-density plastic
HHV	High heating value
LHV	Low heating value
EP_{MSW}	Energy potential of MSW
EPP_{MSW}	Electrical power potential of MSW

Introduction

The management of municipal solid waste (MSW) in the city of Ilorin Kwara state of Nigeria has become a great concern due to the growth of the waste generation rate, on daily basis. The increase in the rate is associated with demographic growth, technological development, urbanization, change in the pattern of fashion and consumption. The waste management system of Ilorin is characterized by inadequate equipment, insufficient manpower, and a lack of the required modern technology. This is noticeably evident by some piles and bales of uncollected MSW, messing up the surroundings of the waste collection centres in the city [1]. In most cities of the developing nations, disposal of waste as a management tool has its deficiencies [2], particularly in the metropolis of Ilorin, due to negligence from the side of the municipalities, lack of equipment, and qualified professionals. The MSW management system practiced in Ilorin includes illegal and unscientific disposal of waste into undesignated sites and open dumps; storage of wastes in skips (called RORO-bins) before collection for disposal to the dumpsite. Ibikunle [3] reported that the MSW fractions in the waste streams produced in the Ilorin metropolis

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include food residue, plastic bottle, nylon (water sachet), polypropylene-sac. Styrofoam, rubber, leather, ceramics, bones, carton, paper, rags, dungs, excrement, toiletries (spent pampers and sanitary pads), wood, grass/trimmings, tins/metals, sand/ash, and other organic matters.

There are several designated dumpsite sites that were officially approved in Ilorin before this study and they include, Eyenkorin site of about 8 ha, Airport Road site of about 5 ha, Oko-Olowo site of about 20 ha, Stadium-road site of about 10 ha, Asa-Dam Road site of about 10 ha, Ita-Nma site of about 4 ha, Madi dumpsite of about 5 ha and Taoheed road site of about 7 ha, as indicated in Fig. 1. The capacity of nearly all the dumpsite sites has been exhausted, and many have been closed, because the neighboring villages to the sites revolted because of pollution and environmental degradation caused by the unscientifically managed dumpsites [4]. Ilorin metropolis functions and operates as the capital city of Kwara state and in the metropolis resides the headquarters for Ilorin East, Ilorin West, and Ilorin local government areas. This also contributes to the high rate of waste generation in the city. Despite the enormous aggregate of MSW generated in Ilorin and the development in WTE technology, there is still an energy crisis in the metropolis. There is a need to embrace an integrated MSW management system that will encourage energy recovery by thermal decomposition, recycling, and other methods to ensure a sufficient waste management system [5, 6]. Renewable energy generation via MSW resources would be a supplement to the insufficient energy supplied by the Power Holding Company of Nigeria (PHCN) in the Ilorin metropolis. This will bring about improvement in the economy of the Ilorin and Kwara state at large. Ogunjuyigbe [7] reported that a green environment and clean energy are crucial to the living standard and the growth of a nation; hence, the need for sufficient and efficient waste management, that embraces reuse, recycling, and recovery of energy cannot be overemphasized.

Renewable energy can be derived from municipal solid waste (MSW) through waste-to-energy (WTE) procedures. WTE processes are appreciable alternatives to other methods of MSW disposal, they also provide favorable options to create alternative fuels via biochemical or thermochemical processes. In the biochemical conversion process, microorganisms break down the MSW components into smaller molecules under anaerobic or aerobic conditions with minimal input of energy. Nevertheless, this biochemical process is slower compared to thermochemical processes, and it is suitable for biodegradable wastes alone. The separation of non-valuable moisture from the products constitutes more problems [8]. Thermochemical conversion is regarded as a destructive process that absorbs a lot of energy, nonetheless, it has some advantages such as reduced usage of water, the shorter cycle of production and the continuity of the operation is easier compared to the biochemical process. Thermochemical processes can be categorized into, incineration (otherwise called controlled combustion), pyrolysis (known as torrefaction at low temperature), and gasification. Incineration is the commonly used WTE technology. The environmental concern and political leverage make it difficult to embark on WTE projects that can be commercialized [9]. Gasification and pyrolysis technologies of MSW are still in the demonstration stages of development for commercial purposes because of inadequate characterization data for MSW that can engender reliable proof of concepts and facility design. MSW components are often characterized and quantified by the source of generation or the type of components that constitute the waste stream. Nevertheless,

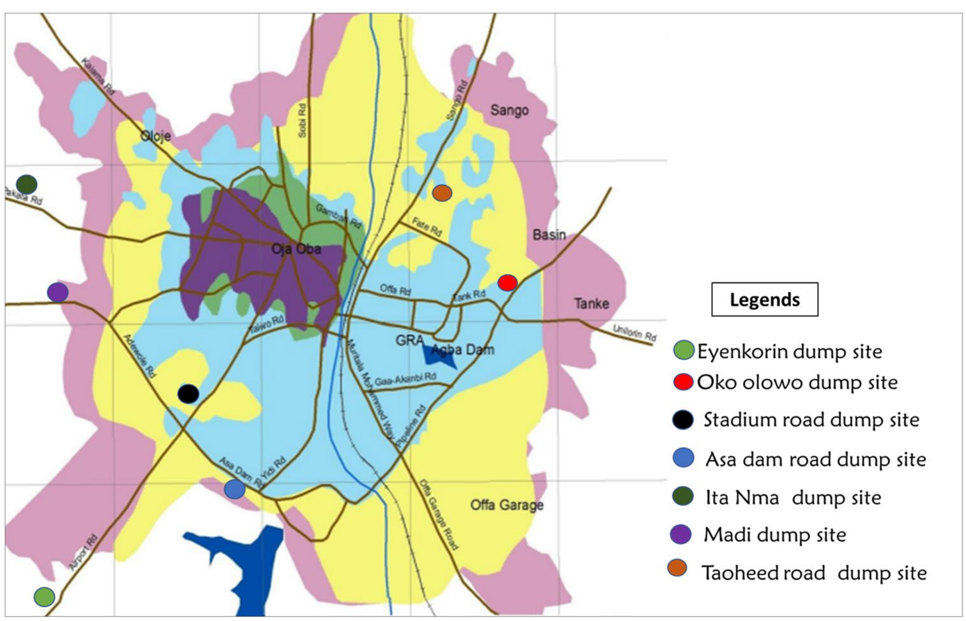

Fig. 1 Map of Ilorin showing some of the locations designated for dump

to design WTE equipment, factors that include percentage volatile matter, moisture content, fixed carbon content; the proportion of combustible and non-combustible waste fractions should be evaluated. These attributes are significant in the selection of the appropriate power plant components, the design (auxiliary) facilities such as flue gas separation equipment, and the suitable WTE technology.

The heating value or the energy content of the MSW components is a very important characteristic of MSW to determine the energy content of the solid fuel [10]. To project MSW generated in the most metropolis of Nigeria for power generation has been difficult, because reliable databases on the waste generation and management procedures in the cities are not available. Therefore, to have an MSW management system that is efficient and sustainable for a WTE technology, it is essential to investigate the waste generation magnitude and the generation rate (kg/person/day) for the dry and the wet season seasons discretely, so as to establish a dependable database for WTE decisions in different seasons [3]. The MSW generated in Ilorin during 2018/2019 dry season (from November 2018 to February 2019), was characterized by Ibikunle [3] to establish that the aggregate MSW produced is about 203,831 tons at the rate of generation 1.12 kg/person/day. He also stated that 280tons of MSW/day, with a low heating value (LHV) of 19 MJ/kg, will generate 1478 MWh of energy and 18 MW of power potential with a grid to the power of 13 kW. It is also important to characterize the wastes streams of a wet season in Ilorin city, to have a dependable database that can be used to project for WTE decisions during the rainy season. Benjamin [11] reported that the detailed characterization of MSW is rooted in the data collection for different seasons, different components, quantities, and rates of generation. Kodo [12] also stated that the data collection for MSW in different seasons is required to anticipate explicative information for MSW management systems. Therefore, this study investigates the aggregate MSW produced during the wet season, the rate of generation, the quantity of the combustible MSW components that can be projected for energy generation, the energy and power potentials of the combustible MSW fractions. This will serve as the database for wet season MSW of Ilorin, which could be adopted as a reliable tool for management plans and decisions to ensure an efficient waste management system and to make a projection for waste-to-energy (WTE) practices in Ilorin.

In the developed nations, WTE technologies have been established with beneficial impact, but the developing nations are yet to implement WTE systems to an in-depth potential, because the sustainability and financial feasibility are still in the trial stage [13, 14]. The waste produced in Ilorin is an enormous one and there is day-to-day developmental growth in the WTE sector; but nonetheless, Ilorin still suffers an energy crisis. The power supplied by Ibadan Electricity Distribution Company (IBEDC) (a sector of the power holding company of Nigeria (PHCN)), is below the capacity required for the socio-economic growth of the metropolis [6]. IBEDC stated in the Blueprint Newspaper of June 16, 2016, that the power requirement of Kwara-State for full-day electricity supply, is about 270 MW [15]. This investigation has established the heating value and the power potential of the wet season MSW in Ilorin to be 23 MJ/kg and 53 MW, respectively. This paper has provided detailed facts on wet season MSW generation in Ilorin for the waste-to-energy option of MSW management. It also reveals that the waste collection rate during the wet season of the year 2020, is about 55% of the collection rate of MSW in the dry season of the year 2018, based on the characterization record of Ibikunle [4]. In this study, it was observed that about 80% of the waste characterized during the wet season is combustible, meaning the WTE process will reduce the quantity of waste dumped by about 80%. Also, the MSW of the season has the potential of meeting about 12% of the Nigeria Renewable Energy Master Plan's target for 2025 and providing about 20% sustainable power demand for Kwara State, based on the projection from Ibadan Electricity Distribution Company (IBEDC) (2016).

The census conducted in 2006 revealed that Ilorin is about 33% of the entire population of Kwara State, this indicates that the capacity of power required by Ilorin metropolis, based on the projection of power requirement for Kwara State by IBEDC in 2016, is about 90 MW, which implies the MSW generated during the wet season can meet about 57% of power demand in Ilorin metropolis. If WTE technology is embraced in Ilorin it will help reduce the aggregate of MSW disposed into the dumpsites and landfills by about 80% and also help the Nigeria Renewable Energy Master Plan (REMP) to achieve their proposed goal of 400 MW of power for 2025 [6]. WTE practices will engender land conservation for useful infrastructures and will also mitigate the production of greenhouse gases (GHGs) from unscientifically maintained landfills [16].

Overview of Ilorin metropolis, Nigeria

Ilorin is the capital city of Kwara state, located in the Western region of Nigeria; at latitude 8° 24′ N and 83° 6′ N of the equator, and along longitude 4° 10′ E and 4° 36′ E of the Greenwich Meridian [4]. According to the 2006 census, Ilorin had a population of about 781,934 people, thereby presenting Ilorin as the seventh-largest city in Nigeria by population (Census, 2006). Ilorin has a projected population of 908,490 people in 2011, with the demographic distribution of 241,040 people for Ilorin East, 243,120 for Ilorin South and 424,330 for Ilorin West hinged on the 2006 census [4, 17]. These data were adopted in predicting the population of the Ilorin metropolis for 2016 to 2022. It has a landed area of about 765 km^2, with Ilorin East Local Government Area occupying about 64.3%, Ilorin West Local Government Area occupying about 14%, and Ilorin South Local Government Area occupying about 23% of the landed area of Ilorin metropolis. The metropolis comprises 35 electoral divisions, viz: 12 wards in Ilorin East, 12 wards in Ilorin West, and 11 wards in Ilorin South. Figure 2 shows the three Local Government Areas that are in the Ilorin metropolis, and how they are bounded by Moro Local Government in the side of the North, by Ifelodun Local Government in the East, by Asa local Government in the West and by Asa and Ifelodun Local Government in the southern part of the metropolis [18]. There are two climatic seasons in Ilorin viz, rainy, and dry seasons. The rainy season considered for this study is between the months of May and August [10]. Olubanjo [19] reported that there is about 0.814 mm downward trend per annum for average rainfall.

Ilorin encounters a high-temperature climatic condition for both the wet and dry seasons. The wet season covers the third month (March) to the tenth month (October) in each year, while the dry season occurs between the months of November of a year to the February of the year that follows. The mean high temperature encountered in Ilorin is 32.5 °C between 1961 and 1990, while 26.2 °C is the daily average temperature. The mean low temperature is 21.2 °C and 1185 mm is the mean rainfall [4]. No less than ten dumpsites were officially approved for municipal solid waste disposal in Ilorin. Eyenkorin dumpsite, which is about 20 acres area of land, located about 25 km from Ilorin along Ibadan–Ilorin expressway; was the only functional and available site for this study. Ibikunle [3] revealed that the MSW waste streams of Ilorin consist mostly of domestic wastes, animal wastes, wastes from commercial centres, and other biodegradable components. The MSW collection system in Ilorin is divided into commercial and social systems. Kwara State Environmental Protection Agency (KWEPA), is the government institution accountable for MSW management of the social system, and the Private Partner Contractors is responsible for waste management of the commercial system in the Ilorin metropolis [4].

Materials and methods

The materials investigated in this research are the MSW fractions contained in the wet season MSW streams. These include household wastes, wastes from institutions, commercial and public centres. Hazardous wastes from hospitals and Industries are not considered. Primary data on MSW generation in Ilorin were collected, using the method suggested by [4] and [20]. Laboratory investigations were performed on the selected combustible MSW components that include packaging box, polypropylene sack, plastic bottle, rubber, wood, grass/garden trimmings, Styrofoam, textile (rags),

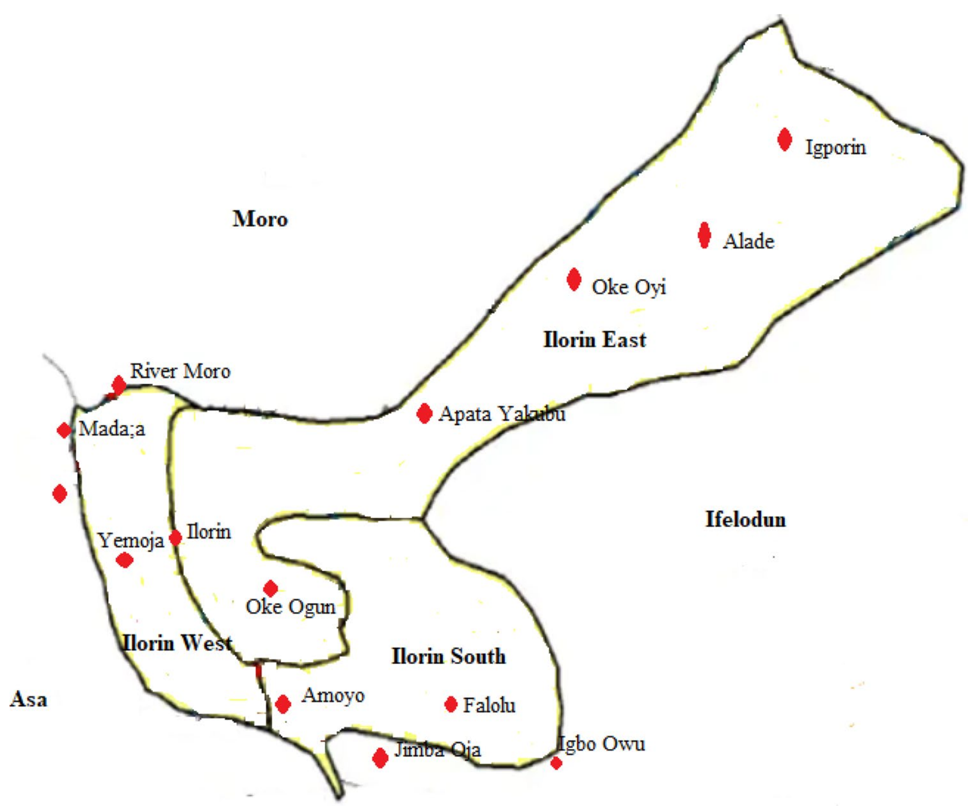

Fig. 2 Map showing some towns and local government areas in Ilorin metropolis

paper, high-density plastic, nylon, food residue, animal bones, and other biogenic components. Ultimate analysis was performed using Flash EA (1112) model of the elemental analyzer and the heating value (HV) was determined using *e 2k* model of combustion calorimeter and the moisture content of each waste fraction was determined using the electrical oven, DHG (9053) of 200 °C capacity model.

Estimation of the population responsible for MSW generation

The population that produces the MSW during the rainy season was estimated using the primary population data (of 2006 census) and the predicted population for 2011, obtained from the National Population Commission (NPC) Ilorin office, were used as the basis to predict the population or 2016 to 2025. The population was predicted by adopting Malthusian mathematical modes in Eqs. (1) and (2) as suggested by Ibikunle [4, 6] and [21]:

$$P_{\text{est}_{(t)}} = P_{\text{pr}_{(t-1)}} \times \left(\mathrm{e}^{(G_r)t} \right), \tag{1}$$

$$G_r = \left[\frac{P_{\text{curr}}}{P_{\text{fmr}}}\right]^{\frac{1}{n}} - 1, \tag{2}$$

where P_{est} is the estimated population of the concerned year (t), $P_{\text{pr}_{(t-1)}}$ is the population prior to the concerned year, G_r is the demographic growth rate per year. P_{curr} is the current population, while P_{fmr} is the former population and n is the number of years involved.

Determination of MSW generated in Ilorin

The aggregate of MSW generated in Ilorin was determined, based on the collection facts and figures, which include the number of collection vehicles/trucks engaged, the tonnage and volume capacity of each truck, the volume rate of loading in each truck, and the amount of trips/truck/day. The mathematical model in Eq. (3), was adopted in the absence of weighbridge as suggested by Titiladunayo [1], Kawai and Tasaki [22] and Ibikunle [10]:

$$\text{MSW}_{\text{coll.}} = \sum_{j=1}^{365} \sum_{i=1}^{n} \left(C_{T_i} \times V_{R_i} \times \rho_i \times t_{n_{ij}} \right), \tag{3}$$

where $\text{MSW}_{\text{coll.}}$ is the amount of MSW collected, n is the available number of collection trucks, the volume capacity of truck is C_{T_i} (m^3 /truck), the volume loading ratio per truck is V_{R_i}, density of MSW loaded/truck is ρ_i (tons/m^3), and the total trips/truck i on day j is $t_{n_{ij}}$ (trips/day).

According to the investigation reported by Ogunjuyigbe [7], only about 74% of the waste generated in the developing nations are collected for disposal, and as adopted by Ibikunle [3]; consequently, the amount of MSW generated in Ilorin was estimated by adopting Eq. (4).

$$\text{MSW}_{\text{gen.}} = \sum_{j=1}^{365} \sum_{i=1}^{n} \left(C_{T_i} \times V_{R_i} \times \rho_i \times t_{n_{ij}} \right) \times \frac{100}{74}. \tag{4}$$

The MSW generation rate was predicted according to Atta23] and Ibikunle [4] by applying Eq. (5):

$$\text{MSW}_{\text{rg}} = 1000\ \text{MSW}_{\text{agg}i} / \left(P_i \times 365 \right) \tag{5}$$

where $\text{MSW}_{\text{agg}(i)}$ is the aggregate waste generated (tons/annum) in year i, MSW_{rg} is the MSW rate of generation (kg/inhab/day), P_i is the population in the year i.

Physical categorization of MSW components

Waste streams produced in Ilorin were characterized during the wet season for four (4) months. The period covers a span from the fifth month (May) to the eight-month (August) 2020. The investigation took place at the Eyenkorin dumpsite, at the rate of two times (Tuesday and Saturday) every week for sixteen (16) weeks; thereby giving thirty-two (32) samples for characterization as suggested by Sharma [24] and Ibikunle [3]. The waste fractions were collected from different heaps of dumps in the site based on the standard of ASTM D5231 [1], and [6]. Subsets of samples are collected from about twelve (12) different heaps of waste and pulled together to give a 240 L of bin waste fractions as a standard sample [10]. This is repeated to have 32 samples. Each of the samples collected was manually sorted into different MSW components that are presented in Table 3. Each identified component was put into different receptacles and was weighed to ascertain the weight of different fractions in a sample and in a batch. About 135,882 tonnes of MSW was produced during the wet season compared to 150,835 tonnes of waste produced during the dry season of 2018–2019 [4] compared to about 302,000 tonnes of wholistic characterization of Ilorin MSW in 2016. During the wet season characterization of MSW, just about 100,553 tonnes was collected for disposal into the dumpsite leaving about 26% of the MSW generated uncollected. The MSW collection rate in Ilorin during the wet season was at an average of about 824 tonnes/day, with a generation rate of about 0.94 kg/inhab/day.

Conduction of ultimate analysis on the MSW components

The percentage components of the chemical elements in the MSW fractions, which include hydrogen, carbon, nitrogen, Sulfur, and oxygen were analyzed by utilizing the Flash EA

1112 Elemental analyzer, based on the ASTM D5291 standard [1, 6]. About 0.5 g of dried powdered samples of each waste component were measured into a crucible and then combusted. The flue produced was channeled into a chromatography section to distinguish the oxides of hydrogen, nitrogen, sulfur, and carbon formed using a thermal conductivity detector (TCD). The electrical signal initiated was processed by software (Eager 300), to give the percentage content of carbon, nitrogen, sulfur, and hydrogen elements that are available in each component. The samples of each waste component were repeated thrice for the experiment, and the average of the values obtained is considered the typical value in Table 4.

Prediction of the heating value of the MSW

The high heating value (HHV) of the MSW fractions was determined experimentally by using the *e2k* model of a combustion calorimeter based on the ASTM D5468-02 standard as suggested by Shi [1, 4, 8]. The values of the HHV obtained via experimentation is input to the models in Eq. (6) as suggested by Shahab [25] and in Eq. (7) as suggested by Ibikunle [6] and [10], to predict the low heating value (LHV). The mean value of Eqs. (6) and (7) is taken as the typical LHV. The HHV of fuel, also called gross calorific value (GCV) obtained from bomb calorimeter, is the quantity of heat released by some quantity of fuel at 25 °C, and when combusted, the products return to a temperature of 25 °C, considering the latent heat of vaporization of water in the combustion products. The LHV, also called net calorific value (NCV), of a fuel is the quantity of heat produced when a specified quantity of fuel at 25 °C is combusted and the temperature of the product of combustion is to 150 °C, assuming the latent heat of vaporization of water in the product is not recovered.

$$\mathrm{LHV}^{a} = \mathrm{HHV}_{\mathrm{msw}}(1 - M) - 2.447M, \tag{6}$$

$$\mathrm{LHV}^{b} = \sum_{1}^{9} \mathrm{Wt.\%} \times \mathrm{HHV}_{\mathrm{msw}}. \tag{7}$$

In Eqs. (6) and (7), LHV^a and LHV^b is the low heating value, $\mathrm{HHV}_{\mathrm{msw}}$ is the high heating value of MSW obtained from combustion calorimeter, Wt.% is the weight percentage of each MSW fraction, while M is the percentage moisture content of the waste components.

Prediction of energy and power potentials of rainy-season MSW streams

Energy and power potentials of the selected combustible MSW fractions of wet season, was predicted by adopting Eqs. (8) and (9), respectively, according to Lawal [6, 10, 26]:

$$EP_{msw} = LHV_{msw} \times w_{msw} \times \frac{1000}{3.6} \ \mathrm{(kWh)} \tag{8}$$

where $\mathrm{EP}_{\mathrm{msw}}$ (kWh) is the energy potential; W_{msw} (tons) is the MSW considered for energy production and $\mathrm{LHV}_{\mathrm{msw}}$ is the typical low heating value (MJ/kg) of the MSW and (1 kWh = 3.6 MJ) is the energy conversion ratio:

$$EPP_{msw} = LHV_{msw} \times \frac{w_{msw}}{24} \times \frac{1000}{3.6} \times \eta \quad \mathrm{(kW)} \tag{9}$$

where $\mathrm{EPP}_{\mathrm{msw}}$ is the power potential; the converting efficiency (η) for power plant, in this study is 30%.

Results and discussion

The demographic distribution of Ilorin metropolis

The National Population Commission (NPC), reported that the population of Ilorin in the 2006 census, was 781,934, and it projected a population of 908,490 people for 2011. These facts formed the basis of the population prediction for the years 2016 to 2025. The demographic growth rate was determined to be 0.03 and the population estimated for 2020 is 1,190,118. The demographic distribution for 2020 is 315763 people in Ilorin East, 555,871 people in Ilorin West, and 318,467 people in Ilorin South. The population distribution shows that about 47% and 27% of MSW generated in Ilorin are produced by Ilorin West and Ilorin South, respectively if Ilorin people have the same pattern of fashion and consumption. The population estimation can be used to predict the expected rate of waste production in 2025 to be 1322 tons/day, if the growth rate, economic activity consumption remain the same. The estimated population is used to determine the MSW generation rate (kg/ihab/day).

Estimation of the quantity of MSW collected in the absence of a weighing machine

The aggregate of MSW generated and the percentage collected were predicted using the models in Eqs. (3) and (4) when the weighing machine. The MSW generated during the wet season of (May–August) 2020, is 135,882 tons as presented in Table 1, compared to the 203,831tons, of MSW reported by Ibikunle [4], for the 2019/2020 dry season of November (2019) to February (2020). This can also be compared to the 3,066,672 tonnes of Lagos, 1,880,112 tonnes of Kano, and 1,624,692 tonnes of Ibadan [27–30]. It implies that the waste generated during the wet season under investigation is about 67% of the MSW produced during the dry season. The reduction in aggregate waste production could be as a result of the lockdown policies and practices during

Table 1 The collection trucks and the quantity of MSW collected in the wet season

Collection trucks	Number of trucks/day	Capacity of Truck (tons)	Capacity of Truck (m^3)	Loading volume ratio	Density of MSW (tons/m^3)	Number of trips/truck/day	MSW collected (tons/day)	MSW generated (tons)
Dinno tipper truck	5	20	16	0.95	1.25	3	34,675	46,858
Hippo tipper truck	3	25	22	0.95	1.136	3	25,998	35,132
Scannia compactor	2	30	22	0.95	1.364	2	13,874	18,748
Arm roller	3	15	8	0.95	1.875	5	26,006	35,144
Total	13	90	68	0.95	5.625	13	100,553	135,882

the coronavirus disease pandemic (COVID-19). The collection facts and figures, show that just 74% of the waste generated was collected for disposal. No wonder, most of the waste collection points in Ilorin are littered with piles and bales of uncollected waste.

The physical categorization of MSW components

The components of waste streams in Ilorin were characterized on the dumpsite for 4 months, and it was established that the MSW streams contain waste components that include, paper, packaging box, grass/garden trimmings, wood, food residue, other biogenic fraction, polypropylene sac, nylon, plastic bottle, high- density plastic (HDP), rubber, Styrofoam, textile (rags), toiletries, excreta, cow-dung, animal bones, leather, tins/metals, sand/ash and glass/ceramics as presented in Table 2. This is compared to plastic, food waste, miscellaneous organic, textile, tin cans, paper, metals, glass, wood, and leather of Port Harcourt [31], palm kernel shell, wood, palm kernel fibre, leather, plastic, rubber, paper, textile carton, and polyethylene of Benin [32], and plastic, polyethene, tyres, polystyrene, leaves, paper, cardboard, and mixed MSW of Ibadan [27].

About 2209 kg weight and 7.68 m^3 volume of MSW were characterized during this study. The quantity of MSW generated increases from the month of May to August, which is evident by the quantity of MSW characterized along the period of the investigation. In May, the quantity

Table 2 Analysis of the characterization of the MSW streams for 8 months

S/N	MSW components	May wt. (kg)	June wt. (kg)	July wt. (kg)	Aug wt. (kg)	Total wt. (kg)	Wt. %	Vol. (m^3)	kg/capita/day
1	Food residue	31.2	56.5	59.2	66.0	212.9	9.64	0.74	0.09
2	Wood	8.30	9.00	18.9	10.7	46.9	2.12	0.16	0.02
3	Paper	23.3	15.5	35.0	28.7	102.6	4.64	0.36	0.04
4	packaging box	60.0	47.5	51.2	63.0	221.7	10.04	0.76	0.09
5	Grass/garden trimmings	22.8	27.6	38.9	41.9	131.2	5.94	0.46	0.06
6	Textiles (rag)	34.5	29.8	26.6	60.4	151.4	6.85	0.52	0.06
7	Toiletries	33.7	22.8	28.4	19.7	104.7	4.74	0.37	0.04
8	Faeces	7.70	19.4	8.84	8.00	43.94	1.99	0.15	0.02
9	Cow dung	11.7	13.4	14.4	3.80	43.29	1.96	0.15	0.02
10	Nylon (water sachet)	58.4	66.8	43.1	41.8	210.1	9.51	0.73	0.09
11	polypropylene sack	24.7	24.1	28.1	39.4	116.4	5.27	0.40	0.05
12	Plastic bottle	70.5	48.4	26.6	37.4	182.9	8.28	0.64	0.08
13	Rubber	4.38	4.80	8.84	7.96	25.98	1.18	0.09	0.01
14	Styrofoam	17.6	9.90	10.0	14.3	51.86	2.35	0.18	0.02
15	High-density plastic	23.5	27.1	12.4	9.24	72.22	3.27	0.25	0.03
16	Leather	3.11	3.64	4.60	5.24	16.59	0.75	0.06	0.01
17	Glass/ceramics	9.50	10.8	14.7	16.1	51.12	2.31	0.18	0.02
18	Animal bones	9.30	13.2	26.3	16.0	64.86	2.94	0.23	0.03
19	Tins/metals	45.2	32.6	27.0	19.1	123.9	5.61	0.43	0.05
20	Sand/ash	12.5	16.6	12.7	10.7	52.43	2.37	0.18	0.02
21	Other biogenic	29.9	43.5	52.4	56.0	181.8	8.23	0.63	0.08
	Grand Total	542	543	548	578	2209	100	7.68	0.94

of waste characterized was 542 kg and it increases continuously to 578 kg in August. The reason for an increase in the waste across the wet season investigated could be the waste increases as the new agricultural products from farms emerges. The largest waste component that is available in the waste streams is the packaging box, which is 10.04% of the wastes characterized, followed by food residue of 9.64%. The smallest waste fraction is leather with 0.75%. The reason for packaging box (carton) to be the commonest waste fraction, could be people consume more of items that are packaged in cartons, which include processed food and drinks, and electronics which keeps them sustained during the COVID-19 lockdown. Leather fraction is the smallest, because leather material is a valuable item in Ilorin used for different ornamental works, shoes, sheath, and the rest; therefore, it is scarce to come by its waste. The MSW generation rate is determined to be 0.94 kg/ihab/day, compared to 0.78 kg/ihab/day of 2017 reported by Ibikunle [6]; it can also be compared to the waste production rate of 0.63 kg/ihab/day in Lagos, 0.58 kg/ihab/day in Kano, 0.51 kg/ihab/day in Ibadan [27–29], and [30], also compared to 1.34 kg/ihab/day in the United Kingdom, 2.13 kg/ihab/day in the United States, 2.00 kg/ihab/day in South Africa, 0.09 kg/ihab/day in Ghana and 0.58 kg/ihab/day in Nigeria as reported by Kawai [22] and Ibikunle [6].

The correlation between the weight distribution, and the generation rate of waste components in Fig. 3, reveals that nylon, food residue and packaging box have the highest generation rate of 0.09 kg/ihab/day with a weight distribution range of 9.51–10.04%. Followed by other biogenic fractions and plastic bottles at 0.08 kg/ihab/day rate of generation with the weight distribution of 8.23 and 8.28% respectively. Grass/garden trimmings and textile (rags) are produced at the rate of 0.06 kg/ihab/day with a weight distribution of 5.94 and 6.86% discretely. Polypropylene sac and tins have a generation rate of 0.05 kg/ihab/day and the weight distribution of 5.27 and 5.61% individually. Leather and rubber components have the smallest generation rate of 0.01 kg/ihab/day with a weight distribution of 0.75 and 1.18% considerately. Table 3 shows the fourteen (14) combustible MSW components considered in the wet season for energy production. It reveals that the aggregate combustible waste

Table 3 The combustible MSW components collected for energy production

S/N	MSW components	wt%	MSW collected (tons)	Vol. (m^3)
1	Food residue	9.64	9692.96	0.74
2	Wood	2.12	2134.87	0.16
3	Paper	4.64	4669.41	0.36
4	packaging box	10.04	10,091.72	0.76
5	Grass/garden trimmings	5.94	5974.00	0.46
6	Textiles (rag)	6.85	6890.77	0.52
7	Nylon (water sachet)	9.51	9562.78	0.73
8	polypropylene sac	5.27	5299.40	0.40
9	Plastic bottle	8.28	8326.46	0.64
10	Rubber	1.18	1182.60	0.09
11	Styrofoam	2.35	2360.65	0.18
12	High density plastic	3.27	3287.43	0.25
13	Animal bones	2.94	2952.41	0.23
14	Other biogenic	8.23	8273.66	0.63
	Grand Total	80.26	80,699.13	7.68

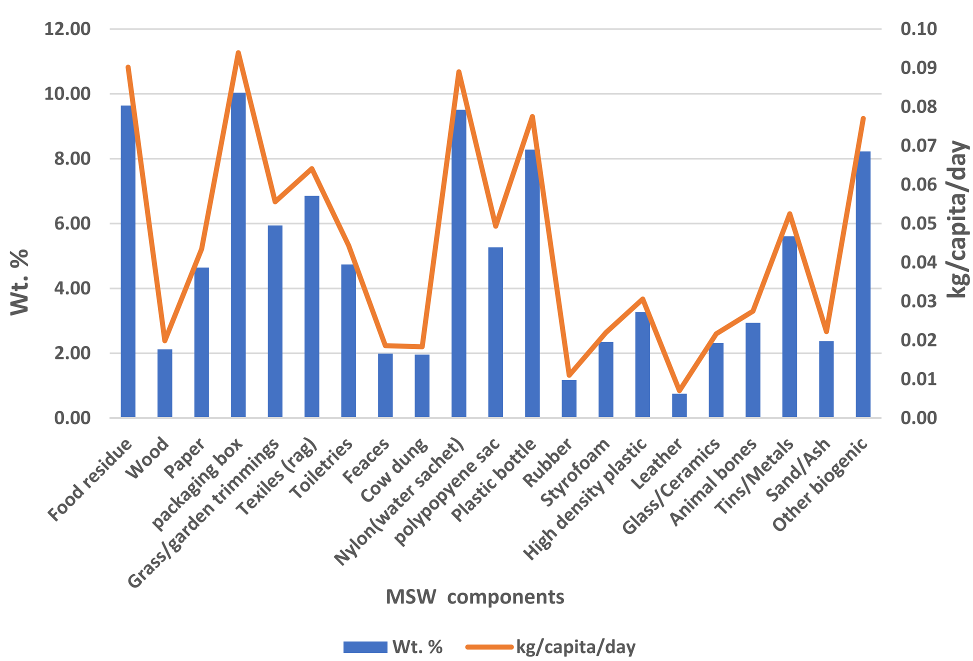

Fig. 3 The correlation between MSW distribution and the generation rate

fractions collected for disposal during the wet season are about 80,700 tons, which is about 80% of the total MSW collected during the entire rainy season. The volume of the combustible fractions of the MSW collected is about 8 m^3 and the aggregate of combustible MSW available for energy generation is about 672 tons/day.

Physicochemical and thermal characterization of MSW components

The physicochemical and thermal analysis of waste fractions in Table 4 shows that the average carbon content present in the combustible wastes investigated is about 55%, while the hydrogen element is about 7%. About 1.4% of nitrogen element, about 0.4% of sulphur content and 30% of oxygen. The combustible waste fractions, is about 80% of the total MSW components characterized, with HHV of about 25 MJ/kg compared to 25.6 MJ/kg and 27.3 MJ/kg, of dimethoxy methane (DMM) and bituminous coal, respectively. The LHV of the MSW is about 23 MJ/kg compared to 22.14 MJ/kg in Port Harcourt [31], 11.85 MJ/kg in Yola [33], 17. MJ/kg in Ibadan [27], and 21.6 MJ/kg in Astan [34]. The LHV of MSW is compared to 20 MJ/kg and 26 MJ/kg of methanol and ethanol, discretely. The 23 MJ/kg LHV of the MSW fractions in Ilorin is equivalent to 49% of energy in petrol, 52% of energy in diesel, 44% of energy in methane and 115% of energy in woody biomass [35].

The distribution of the energy content in the MSW components in Fig. 4, shows that Nylon, has the highest LHV of 45 MJ/kg with 13.95%, followed by polypropylene sac of 42 MJ/kg with 12.89%, and food residue has the lowest LHV of 1.52 MJ/kg with 0.47%. It is observed that the

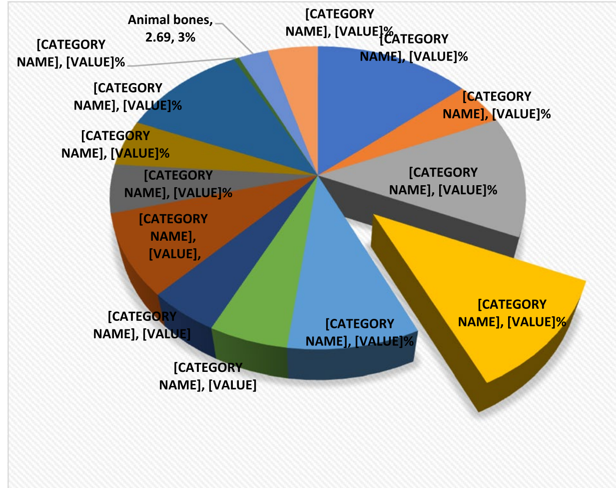

Fig. 4 LHV distribution of MSW components

components with higher LHV have lower moisture contents of 1.03 and 1.02% correspondingly, while components with lower LHV, such as another biogenic component with 14.5 J/kg, animal bone with 8.71 MJ/kg, and food residue with 1.52 MJ/kg, have a moisture content of 15%, 39% and 6.01% appropriately, as represented in Fig. 4. Figure 5 reveals that plastic bottle that have the highest weight percentage of 8.28, have a moisture content of about 0.11%, followed by other-biogenic waste of 8.23% by weight and 15% moisture content, followed by grass/garden trimmings with a weight percentage of 5.94 and a moisture content of 12.32%, and animal bones have the least weight percentage of 2.94 and a moisture content of 39%.

Table 4 Physicochemical and thermal characterization of combustible MSW components

S/N	Waste fractions	Ultimate analysis					Wt %	M %	HHV	LHV
		C %	H %	N %	S %	O %			(MJ/kg)	(MJ/kg)
1	Nylon	29.90	1.06	3.08	0.22	4.16	9.51	1.03	45.6	45.14
2	Packaging box	43.32	5.60	0.65	0.22	41.9	10.0	5.01	15.9	14.94
3	polypropylene sack	76.39	11.8	1.11	0.35	2.62	5.27	1.02	42.2	41.71
4	Plastic bottle	74.97	13.1	0.32	0.62	6.89	8.28	0.11	37.7	37.66
5	Rubber	78.77	7.93	1.34	1.99	6.87	1.18	1.12	29.3	29.02
6	Wood	46.90	5.99	0.50	0.33	44.7	2.12	8.13	19.1	17.35
7	Grass/trimmings	45.81	5.98	2.02	0.26	43.5	5.94	12.32	18.0	15.56
8	Styrofoam	58.71	8.23	0.92	0.20	32.6	2.35	1.05	28.8	28.48
9	Textile (rags)	50.61	5.38	0.93	0.29	43.9	6.85	3.06	17.4	16.77
10	Paper	43.93	6.18	0.32	0.17	47.2	4.64	6.10	17.1	15.92
11	High density Plastic	78.79	12.18	0.31	0.16	11.5	3.27	1.03	36.8	36.42
12	Food residue	50.89	6.95	4.17	0.72	39.1	9.64	6.01	1.82	1.52
13	Animal bones	42.58	4.39	2.03	0.21	39.4	2.94	39.0	15.8	8.71
14	Other biogenic	41.69	4.85	1.24	0.38	49.0	8.23	15.0	17.6	14.5
	Total	763.3	99.62	18.9	6.12	413	80.2	100	343	322
	Average	54.52	7.12	1.35	0.44	29.5			24.5	23.1

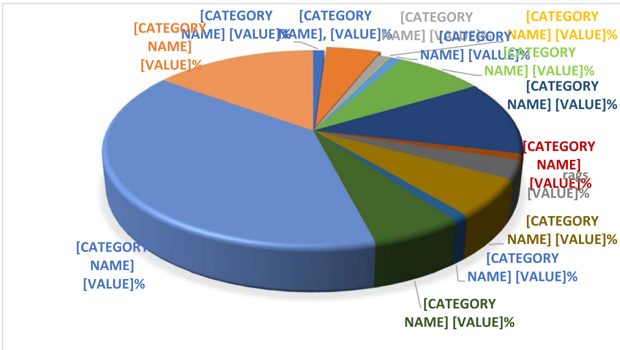

Fig. 5 Moisture content distribution of MSW components

Table 5 shows that the combustible MSW considered for energy generation is 82% of the total MSW collected with fossil resources and kitchen wastes inclusive, which is about 672 tons of waste fractions per day. This is, compared to 30% of the MSW fraction generated in Austria, that is combustible in 2010; and to about 38% of that of Germany, and about 37% of Belgium also compared to the 12% of that of UK [36]. The fossil wastes and biogenic wastes account for about 45% of the combustible wastes selected. Therefore, the combustible wastes outside of fossil products and other biogenic wastes make up about 37% of the aggregate wastes characterized. The average LHV of the waste investigated is 23 MJ/kg. The 672 tons of MSW having a LHV of 23 MJ/kg can produce heat energy potential of 4.2 GW/h and an electrical power potential of about 53 MW, compared to 4.83 MWh in Abuja [37] and 54.2 GWh in Lagos [38]. The energy potential (4.2 GWh) of the MSW fractions, which has a power potential of 53 MW, an equivalent energy potential of about 803 tons of dry wood, 526 tons of coal, 468,523 L of petrol, and 425, 250 L of diesel [6, 35]. The power potential (53 MW) of MSW compared to 4.730 MW of fossil fuel power capacity in Nigeria as of 2013 [39], which appropriates about 15.6 MW of fossil fuel capacity to Kwara State, and Ilorin metropolis will have access to about 0.086 MW of fossil fuel capacity by population proportionality. Akorede [40], estimated about 100 MW of power capacity of biomass in Nigeria. This will mean about 0.33 MW of capacity of biomass in Kwara State, and about 0.0182 MW in Ilorin by population proportionality.

Conclusion

An extensive quantity of waste is generated in the Ilorin metropolis, and the waste management system available is insufficient, which engenders unmethodical disposal of MSW that accounts for environmental contamination. The categorization of waste streams, using 32 samples of 240 L bin volume of MSW for four months of the wet season shows that about 135,822 tonnes were produced at a rate of 0.94 kg/ihab/day. Notwithstanding, 100,553 tonnes of MSW were collected for disposal at a rate of about 838 tonnes/day. The amount of combustible waste components available for energy projection is 672 tonnes/day, which is about 82% of the entire MSW produced in the wet season. It is established that 672 tonnes of MSW at 23 MJ/kg LHV, will generate an energy potential of 4.2 GWh and 53 MW of power potential. The MSW with an energy content of 23 MJ/kg, will produce a correspondent energy that is about 49% of the energy in petrol, 52% of the energy in diesel, 44% of the energy in methane and 115% of energy in woody biomass

Table 5 The distribution of energy (EP_{MSW}) and power (EPP_{MSW}) potentials of combustible MSW

S/N	MSW components	Wt. %	MSW (tons) collected	Vol. (m^3)	MSW/day (tons)	LHV (MJ/kg)	EP_{MSW}(kWh)	EPP_{MSW} (kw)
1	Food residue	9.64	9692.96	0.74	80.77	1.52	34,104.9	426.31
2	Wood	2.12	2134.87	0.16	17.79	17.35	85,740.9	1071.76
3	Paper	4.64	4669.41	0.36	38.91	15.92	172,076.4	2150.96
4	packaging box	10.04	10,091.72	0.76	84.10	14.94	349,005.2	4362.57
5	Grass/garden trimmings	5.94	5974.00	0.46	49.78	15.56	215,174.8	2689.68
6	Textiles (rag)	6.85	6890.77	0.52	57.42	16.77	267,495.9	3343.70
7	Nylon (water sachet)	9.51	9562.78	0.73	79.69	45.14	999,221.7	12,490.27
8	polypropylene sac	5.27	5299.40	0.40	44.16	41.71	511,662.2	6395.78
9	Plastic bottle	8.28	8326.46	0.64	69.39	37.66	725,867.0	9073.34
10	Rubber	1.18	1182.60	0.09	9.86	29.02	79,442.4	993.03
11	Styrofoam	2.35	2360.65	0.18	19.67	28.48	155,628.2	1945.35
12	High density plastic	3.27	3287.43	0.25	27.40	36.42	277,148.8	3464.36
13	Animal bones	2.94	2952.41	0.23	24.60	8.71	59,526.5	744.08
14	Other biogenic	8.23	8273.66	0.63	68.95	14.5	277,703.8	3471.30
	Grand total	80.26	80,699.13	7.68	672.49	Avg. = 23	4,209,799	52,623

[6, 41]. If the (53 W) power potential of wet season MSW is utilized (compared to 0.086 MW of fossil fuel capacity, and about 0.0182 MW biomass power capacity in Ilorin by population proportionality), it will meet about 59% of the power demand in the Ilorin metropolis [42] and help meet about 12% of the Nigeria Renewable Energy Master Plan (REMP) goal for 2025. Waste-to-energy (WTE) method can be considered as the better option for a sustainable and efficient waste management system in Ilorin, because it will reduce the amount of waste disposed to dumpsites and landfills by about 80%, and as well, serve as a source of renewable energy that can complement the power supplied by the Nigeria Power Holding Company.

Recommendation

WTE method of waste management is recommended for Ilorin metropolis as the better option because about 80% of the MSW generated is combustible with a heating value (HV) ≥ 23 MJ/kg and generation rate of about 0.94 kg/ihab/day. This inferred that waste disposal to either dumpsite or landfill is reduced by ≥ 80% of the MSW generated, and it will encourage efficient MSW management via waste components as an energy resource. It will also encourage recycling, reuse, and recovery of energy from MSW fractions. Nonetheless, the waste components have to be treated before transformation to mitigate pollutant precursors that include nitrogen and other elements. The environment of the incinerating plant should be controlled with a technology that contains a precipitator and activated carbon absorbent to control emitted flues and particles.

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Availability of data and materials The available data in this article is the primary data collected during the study.

Declarations

Conflict of interest The author declares that he has no affiliation with or involvement in any organization or entity with any financial interest or non-financial interest in subject matter or materials discussed in this manuscript. I declare that there is no conflicting or competing interests with anyone whatsoever, that could have appeared to influence the work reported in this paper.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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