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Characterization and projection of dry season municipal solid waste for energy production in Ilorin metropolis, Nigeria

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Abstract

This research investigates the quantity of municipal solid waste produced during the dry season, and its characterization at Eyenkorin dumpsite of Ilorin metropolis, along the Lagos-Ilorin express way. The physicochemical and thermal compositions of the combustible fractions of municipal solid waste were analysed, to ascertain the available calorific value. In this research, the quantity (tonnes) of waste generated, the rate of generation (kg per capita per day), its sustainability and the likely energy and power potentials in the dry season, were essentially predicted. The population responsible for municipal solid waste generation during this study was 1,120,834 people. During the characterization study from November 2018 to February 2019, it was established that 203,831 tonnes of municipal solid waste was produced during the four months of the dry season, at the rate of 1.12 kg per capita per day. It was found that 280 tonnes/day of municipal solid waste with low heating value of 19 MJ kg^{-1}, would generate 1478 MWh of heat energy and 18 MW of electrical energy potentials discretely, and grid of 13 kW.

Keywords

Municipal solid waste, seasonal characterization, compositions, clean and affordable energy, electrical power potential, heating value, waste management

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Introduction

The quest for new materials, technological development and the production of diverse items for people's consumption, contribute to the generation of different municipal solid waste (MSW) components (Guadalupe et al., 2009). In the developed nations, waste management systems have adopted various kinds of waste management methods; but in contrast, the developing nations rely on the traditional and unscientific waste management system (method) of waste disposal into landfills and open dumps. Landfill method of waste management is popular because of its simplicity and economic advantage over other methods (Bexultan et al., 2019; Renou et al., 2008). Nevertheless, it is characterized by unfavourable environmental consequences and the requirement for a large area of land; therefore, other methods such as thermal degradation of MSW for energy generation are preferred as a waste management solution. To develop a sufficient and efficient waste management system, reliable data on constituents and characteristics of MSW are required, and they vary from one place to another and from dry season to wet season (Bexultan et al., 2019; Denafas et al., 2014; Edjabou et al., 2018).

Consequently such practices lead to the production of greenhouse gases (GHGs) from landfills and dumpsites. These therefore increase the intensity of air and surface water pollution (Titiladunayo et al., 2018). Also, improper and insufficient MSW management systems result in blockage of water ways, obnoxious odour, unsightly scenes and land degradation among others. Prevention and mitigation of the consequential effects of waste production is a great challenge, for both developed and developing nations (Ibikunle et al., 2018). MSW generated in different communities varies in quantity and quality because of different frameworks that include location, standard of living and consumption habits, geographical and environmental conditions. In India, there is a wide diversity in the parameters; therefore, the quality and quantity estimation of waste generation in a particular location cannot be adopted as a management tool for effective decision-making in other cities or metropolises (Anita et al., 2013).

Arriving at a sustainable and efficient MSW management method/system for urban centres has been a difficult task because

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of the demographic distribution, geographic and socioeconomic factors of the cities; these have an impact on the quantity, quality and composition of the waste generated (Ibikunle, 2019). To select an appropriate MSW system that will be reliable and sustainable to cater for waste generation in a city like Ilorin, Nigeria, will require a detailed characterization study to establish the amount and composition of MSW produced. It has been reported that MSW management is a very demanding territorial/environmental issue in the cities of the developing nations around the globe (Jasir, 2020a). In mountainous regions of the north-western Himalayas, only limited studies on waste management are possible because of diverse challenges which include topography and variation in geographical and climatic conditions, thereby making insufficient data available (Jasir et al., 2020b).

Benjamin et al. (2014) reported that the characteristics of MSW are embedded in the types of constituents (fractions), quantity, rate of generation and the season of generation. Kodo et al. (2015) stated that MSW data for every season is required, as a resource to provide an evaluative information for waste management systems. There are two prominent seasons experienced in the city of Ilorin: the rainy and the dry seasons. This study was performed on the comprehensive characterization and analysis of the MSW streams of the dry seasons alone. This is to ascertain the sustainability and sufficiency of the dry season wastes streams for energy production. This paper adopts the background and methodology earlier used by Titiladunayo et al. (2018) and Ibikunle et al. (2019), to characterize and analyse the dry season municipal solid waste generated in Ilorin.

The comprehensive characterization of MSW was performed at Eyenkorin dumpsite, which is about 15 km from Ilorin, along the Lagos-Ilorin express way. This dumpsite was the only approved dumpsite that was operational during this study. Characterization is essential to achieve an efficient waste management system because it enables easy identification of the available waste fractions/components in the waste streams and the sources of generation. This is vital while determining the physicochemical contents of the waste components and the potential thermal and power capacity of the MSW fractions, it also helps in determining the appropriate method for energy recovery from waste streams and also facilitate the parameters required in the design of the power plant needed to convert the waste to energy. In addition, it encourages compliance with laws, policies and regulations established by the waste management sector to ensure a green, clean and healthy environment (Ayeleru et al., 2018; Titiladunayo et al., 2018).

Ilorin metropolis generates a huge quantity of MSW, and the system of waste management in practice is inadequate; thereby encouraging indiscriminate disposal of wastes (Ibikunle et al., 2019). These antisocial and illegal acts often expose the populace to diverse environmental challenges that include unbearable odour, unsightly scenes and the emission of greenhouse gases (GHGs) that also deplete the ozone layer (Titiladunayo et al., 2018). The absence of a MSW generation database limits the waste management system in decision making, and also prevents projections from being made that could adequately provide a sustainable solution for the waste management challenges. It is therefore necessary to investigate the waste generation capacity of the city as well as the generation rate (per capita per day) in the season in question. Through this, the appropriate method to be adopted in managing the MSW of Ilorin metropolis, using the case of dry season analysis, could be ascertained. The waste-to-energy (WTE) method of waste management involves consumption of wastes and the release of green energy; this will reduce reliance on fossil fuel usage (Ibikunle et al., 2019). The integrated municipal solid waste management system encompasses degradation of MSW thermally and recovery of clean energy for power production, which will ameliorate the challenges of power failure (Ibikunle et al., 2018). Data obtained from dry season waste characterization will be useful to determine the appropriate waste disposal facilities and management policy formulation for the season.

Bolanle and Bayonle (2018) reported that there is variation in the types and the bulk of MSW generated in the wet and dry seasons, in Ibadan Oyo State of Nigeria. The waste generated during the dry season is less than that of the wet season; this could be attributed to low agricultural wastes in the season and the propensity of members of the public to take advantage of the dryness in the season to burn some waste fractions, especially paper, leaves/shrubs, rags and others. Also, there is a proclivity for people to consume fewer food items like fruits, maize and vegetables, due to a reduction in the production of such food items during the dry season.

The aim of this study is to produce MSW data for the dry season that will stand as an encompassing resource for an extensive, analytical and evaluative information and template for the waste-to-energy (WTE) option of management methods in Ilorin. Notwithstanding the enormous amount of waste produced in Ilorin and the growth experienced in the WTE sector in the developed nations of the world, the available power in Ilorin supplied by the power holding company of Nigeria (PHCN) is still below the capacity required for the country's socioeconomic growth (Ibikunle et al., 2020). Ibadan Electricity Distribution Company (IBEDC) reported in 2016, that Kwara-State needs 270 MW for 24-hour electricity supply. This study has established the heating value and the energy potentials of the MSW generated during the dry season in Ilorin; moreover it was established that the dry season waste would provide about 6.7% of the power demand in Kwara State; and about 4% of the Nigeria Renewable Energy Master Plan (REMP) goal for 2025. Consequently, waste to energy in Ilorin will guarantee a decentralized power supply system and will also reduce the quantity of waste disposed into the dumpsites/landfills by about 71% (Ibikunle et al., 2019), thereby engendering conservation of land for useful infrastructures and mitigating the effect of carbon dioxide and greenhouse gases (GHGs) that would have been produced from landfills (Wen-Tien and Kuan-Chi, 2010).

Characterization on the dump site will be easier during the dry season when there is no interruption by rain. This will ensure a reliable survey with enough samples, to avoid the tendency for errors due to insufficient samples; to establish the rate of waste collection, rate of disposal, determine the different components available in the waste streams and hence estimate the energy and power potentials therein. The method adopted for dry season MSW investigation can be considered as a template for other seasons.

The study area

The Ilorin metropolis is on latitude 8° 24' N and 83° 6' N, longitude 4° 10' E and 4° 36' E located between the south-western and middle belt of Nigeria (Ajadi and Tunde, 2010). The three local government areas domiciled in the city are Ilorin East, Ilorin West and Ilorin South. The recent population growth in Ilorin makes the city appropriate for this study, because the demographic growth enhances the increase in waste generation rate. The metropolis comprises 35 electoral wards: 12 wards in Ilorin East, with land area of 486 km^2; Ilorin West of about 105 km^2 in area and 12 wards; and Ilorin South of 11 wards and an area of 174 km^2. The National Population commission projects the population of Ilorin to be 908,490: Ilorin East 241,040, Ilorin South 243,120 and Ilorin West 424,330, based on the 2006 census. This data was used to predict the population of Ilorin for 2016 to 2020.

Ajadi and Tunde (2010) reported that the city experiences a very high temperature between November and February considered as the dry season. The people in the city engage in different kinds of trades and professions that include cattle-rearing, trading, civil jobs of different cadres, as well as operations in both formal and informal sectors. The only functional dumpsite among the approved designated location during this research, was Eyenkorin along the Ilorin-Lagos express way. The fractions of MSW characterized in this study include: food residue, plastic bottles, nylon (water sachet), paper, packaging boxes, wood, grass/trimmings, rubber, bones, leather, textile (rags), spent toiletries, polythene sacks, glass/ceramics, tins/metals, and excrement, sand/ash, cow dung and others. The local government areas in Ilorin metropolis – Ilorin West, Ilorin East and Ilorin South – are circled on the map showing the local government areas of Kwara State Nigeria, presented in Figure 1.

Figure 1. Map showing Asa, Moro, Ilorin West, Ilorin South and Ilorin East and other local government areas of Kwara State of Nigeria.

Materials and methods

The materials analysed in this research are MSW components that involve kitchen wastes, commercial wastes and wastes from institutions and public centres. Industrial and hospital wastes were not included. Primary data was collected on MSW generation in Ilorin metropolis, as suggested by Abdellah and Balla (2013). Laboratory analyses were performed only on the combustible waste fractions, using the DHG (9053) model of electrical oven and the TDW model of furnace for proximate analysis. The ultimate analysis was performed using the Flash EA (1112) model of elemental analyser and the heating value analysis using the *e 2k* model of bomb calorimeter.

Estimation of the population accountable for waste generation

The prediction of the population that generate waste during the dry season was achieved by using the population data from the National Population Commission office for Ilorin (Ibrahim et al., 2014), as the basis for the adoption of a model presented in equations (1) and (2) (Ibikunle et al., 2019; Mehmet, 2013).

$$P_t = P_{(t-1)} \times e^{k_p t} \tag{1}$$

$$K_P = \left[\frac{p_{pr}}{p_p}\right]^{\frac{1}{n}} - 1 \tag{2}$$

In equation (1) 't' is the period of the year concerned, the predicted population of the year of interest is P_t, the population of the year prior to the year of concern is $P_{(t-1)}$, and the annual rate of population increase is K_P. In equation (2), the current population is p_{p_t}, the previous population, p_p and 'n' is the number of years considered.

Estimation of the amount of solid municipal waste collected

In a MSW management system where the use of a weigh bridge is not available, Kosuke and Tomohiro (2016) suggested equation (3) as an appropriate model to determine the quantity of MSW collected for disposal (Ibikunle, 2019). The model is based on the data and facts of waste collection processes.

$$MSW_{disposed} = \sum_{j=1}^{365}\sum_{i=1}^{n}\left(C_i \times V_i \times d_i \times t_{ij}\right) \tag{3}$$

In equation (3), the number of trucks engaged is '*n*', the capacity of individual truck is C_i; the volume loading ratio of each truck is V_i; the density (tonnes m^{-3}) of MSW in a truck is d_i; and t_{ij} (rate of trips/day) is the total number of trips performed by each truck in a day.

Estimation of the quantity of MSW generated

It was established by Ogunjuyigbe et al. (2017) that the quantity of MSW collected for disposal in most of the developing nations, is just 74% of the quantity generated. This implies that the quantity of the waste generated per annum can be determined using the model in equation (4).

$$MSW_{gen.} = \sum_{j=1}^{365}\sum_{i=1}^{n}\left(C_i \times V_i \times d_i \times t_{ij}\right)\times\left(0.74\right) \tag{4}$$

Determination of MSW rate of generation

Oumarou et al. (2012) established that the rate of generation of MSW in kg per capita per day can be estimated by using equation (5).

$$MSW_{gen.rate} = \left[\left(\frac{waste\,generated}{weeks}\right)\left(\frac{weeks}{days}\right)\right] / \text{ population} \tag{5}$$

Physicochemical characterization of municipal solid waste

The physicochemical composition of MSW samples was determined using proximate and ultimate analyses. Proximate analysis was conducted to determine the volatile matter, moisture content, fixed carbon and ash contents of the waste constituents; while, the ultimate analysis was performed to determine the percentage compositions of carbon, nitrogen, hydrogen, sulfur and oxygen contents.

Proximate analysis. This analysis determines the moisture content, ash content, volatile matter and fixed carbon contents of the waste samples. The analysis was carried out based on American Standard Test Methods (ASTM) (Ibikunle et al., 2018; Titiladunayo et al., 2018).

Moisture content. Three test samples were measured into dishes to obtain 5 g each, and later poured inside crucibles to be dried in the oven maintained at 105°C for 1 hour based on ASTM D1348. The loss in the weight is taken as the moisture content (Ibikunle et al., 2019; Vairam and Ramesh, 2013).

Volatile matter content. Volatile matter content was determined by heating the test sample used for moisture analysis at 950°C for 7 min, based on ASTM D3175-11. The crucibles containing the samples were withdrawn from the furnace and put in a desiccator to cool down. When weighed, the loss in weight is taken as the percentage volatile matter.

Ash content. Ash content was obtained by igniting the samples left in the crucible after volatile matter analysis, without covering with a lid at 750°C for 30 min, in accordance with ASTM D5468-02. The samples were withdrawn and cooled. The residue left is the ash content.

Fixed carbon. The fixed carbon content is the difference between 100 and the moisture content (%), volatile matter (%), and ash (%) added together, in agreement with ASTM D3172-07a.

Determination of calorific (heating) value

According to earlier submissions (Ibikunle et al., 2019; Titiladunayo et al., 2018), the high heating value (HHV) or calorific value of MSW was verified by using a combustion calorimeter based on ASTM D5468-02 standard (Shi et al., 2016). The mass (0.5 g) of dried and milled sample of each fraction was input through a data logger and was combusted in a bomb of high-pressure atmosphere containing oxygen. After completion, the result was presented on the screen. The average result of the experiments carried out on the replicated samples was regarded as the heating value (MJ kg^{-1}) for each sample. Islam (2017) earlier suggested that low heating value (LHV^a) can be obtained through HHV using equation (6). Nevertheless, the values of chemical elements obtained from ultimate analysis were input into the models developed by Dulong and Steuer shown in equations (7) and (8), respectively, to have low heating values LHV^b and LHV^c, respectively. The average value of the results from equations (6), (7) and (8) is considered as the net low heating value of the MSW.

$$LHV^a = \sum_{1}^{9} W_{\text{msw}} \times HHV_{\text{msw}} \tag{6}$$

$$LHV^b = 81C + 342.5\left(H - \frac{\text{O}}{8}\right) + 22.5S - 6\left(W + 9H\right) \tag{7}$$

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

In equation (6), LHV^a is the low heating value obtained by using values from the bomb calorimeter, HHV_{msw} is the high calorific (heating) value from the combustion calorimeter, W_{msw} is the weight of each waste fraction. In equations (7) and (8), LHV^b and LHV^c are heating values from Dulong and Steuer models, respectively, and the chemical elements (carbon (C), hydrogen (H), sulfur (S) and oxygen (O)) are from ultimate analysis.

Table 1. The predicted demographic distribution of Ilorin metropolis.

Year	Demographic centres of Ilorin metropolis	Population	Total	Source
2011 Projection	Ilorin East	241,040	908,490	National Population Commission (2006)
	Ilorin West	424,330		
	Ilorin South	243,120		
2016 Prediction	Ilorin East	280,049	1,055,515	Mehmet (2013) equations (1) and (2)
	Ilorin West	493,001		
	Ilorin South	282,465		
2017 Prediction	Ilorin East	288,578	1,087,660	Mehmet (2013) equations (1) and (2)
	Ilorin West	508,015		
	Ilorin South	291,067		
2018 Prediction	Ilorin East	297,380	1,120,834	Mehmet (2013) equations (1) and (2)
	Ilorin West	523,510		
	Ilorin South	299,945		
2019 Prediction	Ilorin East	306,413	1,154,878	Mehmet (2013) equations (1) and (2)
	Ilorin West	539,411		
	Ilorin South	309,056		
2020 Prediction	Ilorin East	315,763	1,190,118	Mehmet (2013) equations (1) and (2)
	Ilorin West	555,871		
	Ilorin South	318,487		

Table 2. The collection vehicle and the quantity of waste collected.

S/N	Types of vehicle	Number of trucks/day, l	Capacity/vehicle (tonnes)	Volume/vehicle, C (m^3)	Number of trips/vehicle/days, t	Mean Density of MSW loaded on truck, d (tonnes m^{-33})	MSW generated (tonnes)	MSW collected (tonnes)	MSW collected (tonnes/day)
1	Dino tipper truck	5	20	16	3	1.25	70,286	52,012	143
2	Hino tipper truck	3	25	22	3	1.13	52,715	39,009	107
3	Scania compactor	2	30	22	2	1.36	28,115	20,805	57
4	Arm roller	3	15	8	5	1.87	52,715	39,009	107
	Total	13	90	68	13	1.40	203,831	150,835	414

MSW: municipal solid waste.

Estimation of energy and power potentials of dry season MSW streams

The estimation of energy and power potentials of the combustible waste fractions in the dry season was performed using equations (9) and (10), respectively, according to Daura (2016) and Ibikunle et al., (2019).

$$EP_{msw} = LHV_{msw} \times w_{msw} \times \frac{1000}{3.6}(\text{kWh}) \tag{9}$$

Where the energy potential is EP_{msw} (kWh); the weight of MSW considered for energy production is W_{msw} (tonnes); and the net low calorific (heating) value of the MSW is LHV_{msw} (MJ kg^{-1}). The energy conversion ratio is 1 kWh = 3.6 MJ.

$$EPP_{msw} = LHV_{msw} \times \frac{w_{msw}}{24} \times \frac{1000}{3.6} \times \eta\,(\text{KW}) \tag{10}$$

In equation (10), EPP_{msw} is the electrical power potential; converting efficiency (η) is used for the power plant, with range 20–40%; but 30% is adopted in this study.

Results and discussion

The population distribution for Ilorin metropolis

According to the National Population Commission Ilorin office, the population of Ilorin, from the 2006 census, was 781,934 (NPC, 2006) with a projection of 908,490 people for 2011. Based on these facts and data, the population for 2016 to 2020 was predicted during the study as presented in Table 1. The population liable for MSW production in Ilorin during this study was predicted to be 1,120,834 for 2018 and 1,154,878 for 2019, using equations (1) and (2) (Ibikunle et al., 2019; Mehmet, 2013). The population data obtained was used to determine the per capita waste generation of the season when the quantity of waste generated was established.

The availability of MSW collection vehicles in Ilorin, their capacities and the quantity of wastes collected is presented in Table 2. There are four different types of trucks engaged: Dino Tipper truck, Hino Tipper truck, Scania compactor and Mazda (arm roller) truck. The amount of MSW generated during the four

Table 3. Characterization of MSW streams of the dry season.

Waste fractions	MSW collected (tonnes/season)	MSW generated (tonnes/season)	MSW generated (tonnes/day)	Volume (m³)	Wt. (%)	kg per capita per day
Food residue	9352	12,638	78	0.45	6.20	0.070
Wood	1131	1529	9	0.12	0.75	0.008
Paper	10,483	14,166	87	0.53	6.95	0.078
Packaging box	9367	12,658	78	0.48	6.21	0.070
Grass/trimmings	5777	7807	48	0.45	3.83	0.043
Textiles (rag)	16,818	22,727	140	0.82	11.15	0.125
Toiletries	10,739	14,513	89	0.63	7.12	0.080
Faeces	3062	4138	26	0.12	2.03	0.023
Cow dung	1931	2609	16	0.09	1.28	0.014
Nylon	28,659	38,728	239	1.35	19.00	0.213
Poly (bagco sac)	7735	10,452	64	0.56	5.13	0.058
Plastic bottle	12,519	16,918	104	0.63	8.30	0.093
Rubber	226	306	2	0.12	0.15	0.002
Leather	106	143	1	0.015	0.07	0.001
Glass/ceramics	4646	6278	39	0.42	3.08	0.035
Bones	679	917	6	0.06	0.45	0.005
Tins/metals	7542	10,192	63	0.33	5.00	0.056
Sand/ash	6335	8561	53	0.29	4.20	0.047
Others	13,726	18,549	114	0.68	9.10	0.102
Total	150,832	203,827	1257	8.145	100	1.121

MSW: municipal solid waste.

months of the dry season was estimated to be 203,831 tonnes while 150,835 tonnes of MSW was collected for disposal during the season at the rate of 107 tonnes/day.

Characterization of municipal solid waste

MSW streams from the Ilorin metropolis were characterized for the four months of the November 2018 to February 2019 dry season. The list of MSW components identified is presented in Table 3 and includes food residue, excrement, bones, wood, packaging boxes, paper, grass/trimmings, textile (rags), toiletries (spent diapers, toilet tissue and sanitary pads), cow dung, nylon, polythene (BAGCO sacks), rubber, plastic bottles, leather, ceramics, metals/tins, sand/ash and others. About 203,827 tonnes of MSW was generated during the dry season examined, while about 150,832 tonnes was collected and disposed to the dumpsite, and about 26% of the waste generated was left uncollected. MSW was produced at an average rate of 125 tonnes/day during the season; and the generation rate was 1.12 kg per capita per day. During characterization, the percentage distribution of waste fractions reveals that nylon has the highest fraction at 19%, followed by textiles (rags) 11.15%, plastic bottles 8.3% and toiletries 7.12%, and the lowest fraction is wood (0.75%). The amount of nylon sachets and plastic bottle wastes are high because they are used to package water and other drinks which people desire because of the hot climatic condition of the dry season. The textile (rags) component is also high because people dispose of more of their discarded clothes during the dry season so that they could be burnt on the dump site.

In Figure 2, the distribution of MSW generation rate (kg per capita per day) among components during the dry season is presented to show how regularly each fraction occurs in the waste streams during the period of the characterization study. This authenticates the sustainability of each fraction, and will help in taking decision on the type of waste management method that could be most appropriate in the city. The generation rate of MSW during the dry season is 1.12 kg per capita per day. The nylon fraction is 0.2%, textiles 0.12%, others 0.10%, plastic 0.093% and the lowest is leather at 0.001%. The combustible fractions constitute about 68% of the aggregate MSW generated in the dry season. This is a signal that energy production via thermal degradation of MSW will be the appropriate method of waste management in Ilorin during the dry season.

The combustible waste fractions selected for both laboratory and energy potential analyses form 68% of the entire quantity of MSW characterized. The reason for this selection is based on their regular flow in the waste streams and the characteristic factor in combustion. There are nine waste fractions considered for energy generation as presented in Table 4. About 33,545 tonnes of MSW was estimated as the combustible fraction generated in the dry season, at the rate of 0.758 kg per capita per day, and 280 tonnes/day is the quantity estimated for energy production.

The percentage contents of chemical elements from the ultimate analysis shown in Table 5 reveals that the average carbon (C) content of the combustible waste fractions is 29%, hydrogen (H) content is 0.11%, nitrogen content is 3.49% and sulfur content is 0.43%. Though high carbon content could contribute positively to the heating potential of the waste as an energy resource, nevertheless the percentage distribution of the elemental contents symbolizes the high production of carbon and nitrogen oxides during combustion. The low heating values obtained from the

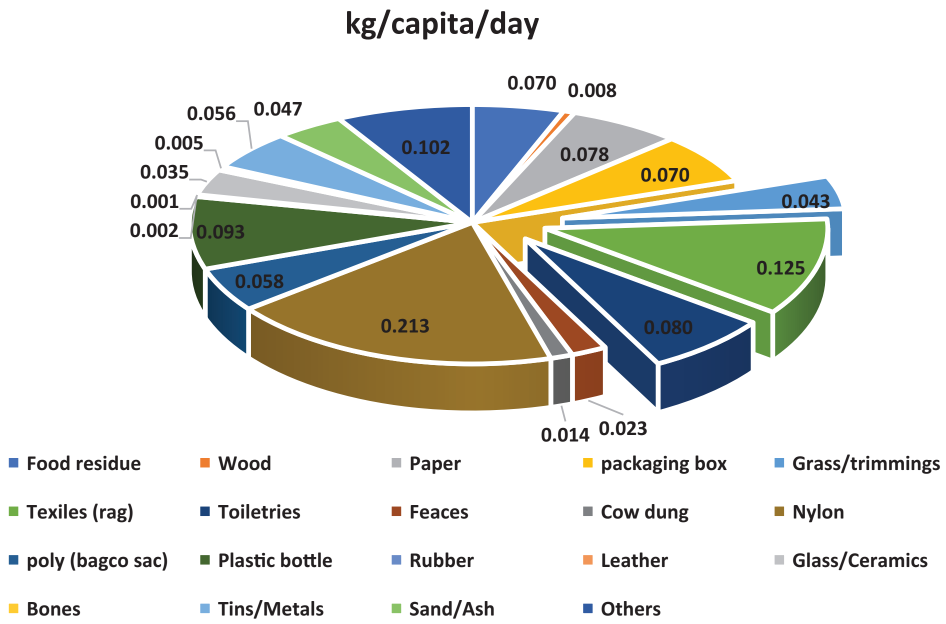

Figure 2. The distribution of the MSW rate of generation (kg per capita per day).

Table 4. The combustible waste fractions considered for energy production.

Waste fractions	Wt. (%)	Dry season MSW (tonnes)	MSW (tonnes/ day)	Volume (m³)	kg per capita per day
Food residue	6.20	3080	25.67	0.45	0.070
Wood	0.75	373	3.11	0.12	0.008
Paper	6.95	3453	28.77	0.53	0.078
Packaging box	6.21	3085	25.71	0.48	0.070
Grass/trimmings	3.83	1903	15.86	0.45	0.043
Textiles (rag)	11.15	5539	46.16	0.63	0.125
Nylon	19.01	9442	78.68	0.12	0.213
Poly (bagco sac)	5.13	2547	21.23	1.35	0.058
Plastic bottle	8.30	4123	34.36	0.56	0.093
Total	67.52	33,545	279.55	0.63	0.758

MSW: municipal solid waste.

Table 5. The percentage chemical contents and the low heating values.

Waste fractions	Wt. (%)	C (%)	H (%)	N (%)	S (%)	LHV¹	LHV²	LHV³
Food residue	6.20	31.23	0.09	3.87	0.13	1.55	1.73	1.95
Wood	0.75	22.21	0.13	2.69	0.07	0.19	0.21	0.24
Paper	6.95	21.05	0.12	2.56	0.12	1.74	1.94	2.19
Packaging box	6.21	36.98	0.08	4.78	3.05	1.55	1.74	1.95
Grass/trimmings	3.83	22.02	0.11	1.89	0.15	0.96	1.07	1.21
Textiles (rag)	11.15	34.81	0.08	4.46	0.11	2.79	3.12	3.51
Nylon	19.01	36.45	0.15	4.38	0.09	4.75	5.31	5.98
Poly (bagco sac)	5.13	33.54	0.12	3.87	0.14	1.28	1.43	1.61
Plastic bottle	8.30	23.08	0.10	2.94	0.05	2.08	2.32	2.61
Total	67.52	261.37	0.98	31.44	3.91	16.88	18.87	21.25

Wt.%: weight of the waste fraction characterized; LHV¹: the low heating value (MJ kg⁻¹) obtained, using Dulong's model; LHV²: the low heating value (MJ kg⁻¹) obtained, using Steuer's models; LHV3: the low heating value (MJ/kg) obtained, using MSW weight (%) and the high heating value (HHV) from bomb calorimeter.

bomb calorimeter, and the application of ultimate analysis values to Dulong's and Steuer's models, are presented as LHV¹, LHV² and LHV³, respectively. The average net low heating value is estimated to be 19 MJ kg⁻¹, which is the heating value used in computing the energy and power potentials of the combustible MSW fractions.

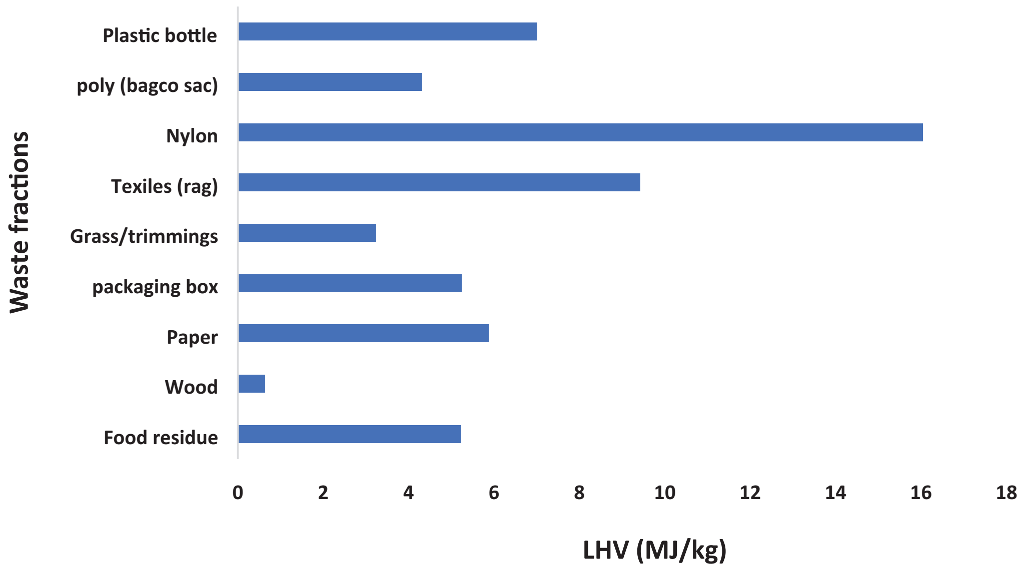

Figure 3. Comparison of the heating values of MSW combustible fractions.

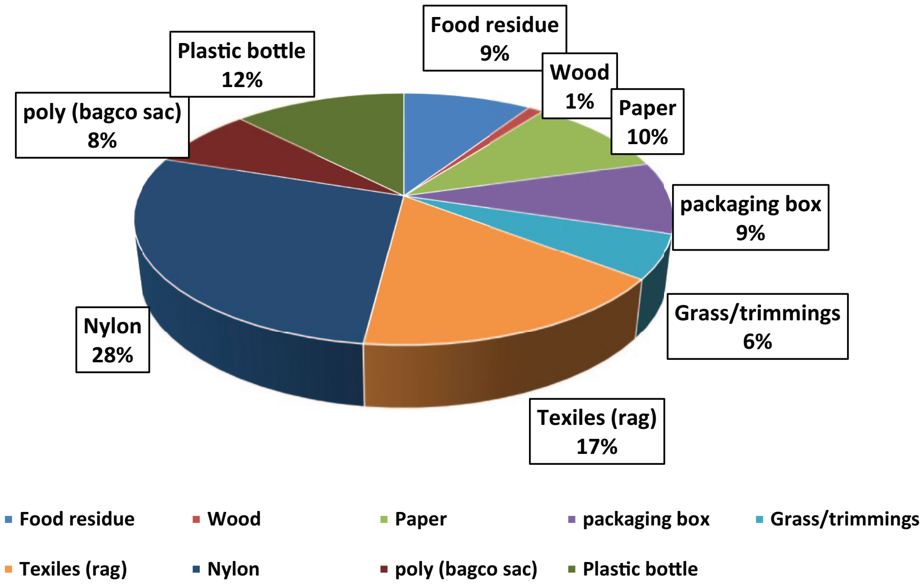

Figure 4. The percentage distribution of energy potential based on heating value.

The comparison of the heating values of the different waste components across the dry season of four months between November 2018 and February 2019 is presented in a clustered bar chart in Figure 3. Nylon fraction has the highest heating value of 16 MJ kg^{-1}, textile (rags) has 9.42 MJ kg^{-1}, followed by plastic with 7.01 MJ kg^{-1} and the lowest is wood at 0.64 MJ kg^{-1}. The high heating value of the nylon waste fraction must have been due to its high carbon content as well as having the highest percentage weight among the combustible waste fractions, while wood has the lowest weight percentage.

The percentage distribution of the MSW energy potential (EPP_{MSW}) based on the net heating value of each waste fraction is presented in Figure 4. Nylon has about 28%, followed by textile with about 17%, plastic of about 12% and the lowest is wood with about 1%.

Table 6 presents the data for energy projection in Ilorin; 280 tonnes of MSW with heating value of 19 MJ kg^{-1} is used to make a projection of 1478 MWh of heating energy, 18 MW of power potential and 13 kW of power to grid.

Conclusion

The amount of MSW produced in the city of Ilorin is enormous, and the available system of management is inadequate, which prompts people to indulge in indiscriminate disposal of wastes that constitutes environmental pollution. The characterization of MSW streams, by considering 32 samples of 240 litres of specific bin volume in each for four months of the dry season reveals that about 203,827 tonnes was generated during the season at the rate of 1.12 kg per capita per day. Moreover, 150,632 tonnes of MSW

Table 6. The predicted energy and power potentials of the municipal solid waste.

Wt. (tonnes/day)	LHV (MJ kg^{-1})	EP_{MSW} (MWh)	EPP_{MSW} (MW)	GP (kW)
280	19	1478	18	13
Conversion ratio				
1000 kg = 1 tonne	10^6 J = 1 MJ	1 kWh = 3.6 MJ	η=30%	η_g = 90% and η_p = 75%

LHV: the typical low heating value (MJ/kg) obtained; EPMSW: the energy potential (MWh) of MSW; EPPMSW: the electrical power potential; GP: power to grid (kW).

was collected for disposal at the rate of 1.256 tonnes/day. The quantity of combustible MSW components available for energy projection is 280 tonnes/day, which is about 68% of the entire MSW generated in the season. It is concluded that 280 tonnes of MSW with heating value of 19 MJ kg^{-1} will produce heating energy of 1478 MWh, 18 MW of electric power potential and 13 kW of power to the grid. The MSW heating value of 19 MJ kg^{-1} will give an equivalent energy of about 41% of petrol, 43% of the energy in diesel, 46% of that of natural gas, 36% of that of methane, 47% of that of coal and about 95% of that of woody biomass (Deep Resource World Press, 2012). The energy potential of MSW, 1.5 GWh, is equal in value to that of 283 tonnes of dry wood, 185 tonnes of coal, 44 tonnes of hydrogen, 165,277 litres of petrol and 150,000 litres of diesel (World Nuclear Association, 2018). The electrical power potential of 18 MW will provide about 6.7% of the power demand in Kwara State (Ibadan Electricity Distribution Company, 2016); and achieve about 4% of the Nigeria Renewable Energy Master Plan (REMP) goal for 2025. The Waste-to-energy method in Ilorin can be contemplated for a sustainable and renewable system, having determined its net heating (calorific) value and energy potential. Consequently, this will guarantee a decentralized power supply system, with MSW as an energy resource. This will also reduce the quantity of waste disposed into the dumpsites/landfills by about 71% (Ibikunle et al., 2019), thereby engendering conservation of land for useful infrastructures and mitigating the effect of greenhouse gases (GHGs) that would have been produced from landfills.

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