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Municipal solid waste sampling, quantification and seasonal characterization for power evaluation: Energy potential and statistical modelling

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ABSTRACT

Municipal Solid Waste (MSW) streams of Ilorin was characterized for four months in each season: May to August 2016, representing wet season; and November 2016 to February 2017 representing dry season. Thirty-two samples of 240 L bin volume of MSW were collected randomly, from heaps of wastes at Lasoju/ Eyenkorin for each season. The samples were manually sorted on the metallic (screening) table (1.5 m × 3 m with 10 mm × 10 mm surface mesh). Nine combustible waste fractions, out of the nineteen waste components characterized, were considered for laboratory analysis. Proximate analysis revealed averages of 57% and 55% fixed carbon content for wet and dry seasons respectively. Ultimate analysis gave 29 and 29.2% total carbon content for wet and dry seasons respectively. Models were developed to ascertain the correlation between the physicochemical properties and the heating values of the waste fractions. The MSW predicted for the dry season was 158 tons/day, with generation rate of 0.15 kg/capita/person, heating value of 29 MJ/kg, energy and power potentials of 890.2 MWh and 11.27 MW, respectively. MSW for wet season was 210 tons/day, with 0.02 kg/capita/day, heating value of 26 MJ/kg, energy and power potentials of 1.1 GWh and 1.06 GW, respectively.

1. Introduction

Municipal Solid Waste (MSW) is defined as the materials generated from different human activities: in households, commercial centres, industries and other institutions [1]; industrial wastes are not inclusive. Egyptian Environmental Policy Programme (EEPP, 2000), defines MSW Management system as that which controls all the activities and policies concerned, in planning, funding, transportation, treating and conversion of municipal solid waste to other materials or energy. The challenge confronting waste management in the urban centres of the developing countries is a significant one because of population growth, industrialization and standard of living [2,3]. MSW generation in Ilorin Kwara State is enormous, and the available management system in the city is insufficient and inefficient; thereby making the city dwellers to indulge in indiscriminate and illegal disposal of wastes into open dumps and waterways [4]. There is no available database on the generation, collection rate and the management processes of the MSW streams of Ilorin Metropolis; therefore, making it difficult to successfully plan for a sustainable and efficient waste management. It is, therefore, needful to investigate the MSW generation capacity and the production rate (kg/capita/day) in different seasons, to establish a reliable database for management plans and decisions. Despite the huge MSW generated in the city, cum the recent development in waste-to-energy technology sector in the developed nations, Ilorin still face power crisis; because their socioeconomic activities depend solely on energy supplied from Power Holding Company of Nigeria (PHCN), which is far below what is

Abbreviations: ASTM, America Society for Testing and Materials; C, Carbon; EP, Energy Potential; EPP, Energy Power Potential; FC, Fixed Carbon; GRETL, Gnu Regression Econometrics and Time-Series Library; HV, Heating Value; HHV, High Heating Value; IBEDC, Ibadan Electricity Distribution Company; IMSW, Integrated Municipal Solid Waste; KMLS, Kwara State Ministry of Lands and Survey; LHV, Low Heating Value; [M], Moisture; MSW, Municipal Solid Waste; N, Nitrogen; O, Oxygen; OLS, Ordinary Least Square; S, Sulphur; TCD, Thermal Conductivity Detector; VIF, Variance Inflation Factor; VM, Volatile Matter; Wt., Weight; WTE, Waste to Energy

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required [5]. Therefore, if the energy and power potentials of the MSW generated in Ilorin are established, then it will be easier for the management to utilize the information in planning and taking reliable decisions on waste-to-energy system concerning the city; this will guarantee an alternative source of power.

Energy recovery from MSW will help to consume wastes and release energy that could reduce reliance on fossil fuel usage [4]. The practice of an Integrated Municipal Solid Waste Management (IMSWM) system that encompasses thermal degradation and energy recovery from MSW for power generation will also reduce the problem of unstable power supply [6]. Data from waste characterization, are paramount for determining the necessary waste disposal facilities and management policy formulation. The data harvested from sampling, characterization and statistical analysis of MSW in Ilorin, will form a reliable basis that will induce energy generation via MSW as an energy resource [7,8]. Thus, the need for the current study.

2. Materials and method

In this research, the waste fractions of the MSW streams, include: food waste, textiles (rag), packaging box (carton), wood waste, paper waste, grass/garden trimmings, toiletries (sanitary pad, toilet tissue and pampers), faeces, cow-dung, nylon, polypropylene (BAGCO sack), plastic bottle, rubber, leather, glass/ceramics, bones, tins/metals, sand or ash and others. They are wastes generated from different households, market centres, institutions, business centres, event centres, parks and yards. Nineteen waste fractions were characterized and nine combustible waste fractions that occur regularly in the wastes streams, were subjected to laboratory analysis, for physicochemical and thermal analyses. Every of the test samples for both dry and rainy seasons was replicated three times for each experiment.

2.1. The study area

Ilorin is the state Capital of Kwara State, Nigeria. located on latitude 8° 24′ N and 83° 6′ N, and longitude 4° 10′ E and 4° 36′ E; The location is between South Western and middle belt of Nigeria [9,6]. The Local Government Areas in the city are: Ilorin East, Ilorin West, and Ilorin South; shown in Fig. 1(a–c), respectively (Kwara State Min. of Lands and Survey, 2009), the city is categorized into traditional, sub-modern and modern areas as presented in Fig. 2(a) (Kwara State Min. of Lands and Survey, 2009). Ilorin metropolis was considered for this study because of its recent growth in population, due to increase in birth rate, industrialization and urbanization. Ilorin East consists of 12 electoral wards with land area of 486 km^2, Ilorin West has 12 electoral wards and land area of 105 km^2, and Ilorin South is made up of 11 electoral wards and an area of 174 km^2. The map of Ilorin showing some sampled political wards is presented in Fig. 2(b) (Kwara State Min. of Lands and Survey, 2009). Apart from increase in birth rate and urbanization, the attack launched by armed insurgents (otherwise called Bokoharam), in the Northern part of the country, has contributed to a tremendous increase in the population of Ilorin city, the North central of Nigeria [6]. Moreover, Ilorin metropolis as the state capital, also accommodates the headquarters of the three local government areas in the city.

The population of the city was projected to be 908,490 in 2011 [10]; and Ibikunle et al [4], predicted the population to be 1,055,515 and 1,087,660 people for 2016 and 2017 respectively. [9], reported that the city exhibits a high-temperature climate both in dry and wet seasons. The wet season in the metropolis is from third month (March) to tenth month (October) and the dry season is between eleventh month (November) and the second month (February) of the following year. The MSW fractions generated in Ilorin includes: Paper, Packaging-box, Food-residue, Plastic-bottle, Nylon, Grass/trimmings, Wood, Rubber, Bones, Leather, Textile (rags), Toiletries (pampers, toilet tissues and sanitary pads), Polypropylene-sacks, Tins/metals, Glass/ceramics, and Excrement (faeces), Cow-dung, Sand/ash and others.

2.2. Collection of MSW samples

A sample in this study refers to the quantity representing the parent waste generated in a MSW stream. Wholistic sampling and characterization of MSW was carried out on-site, at Lasoju dumpsite (the only functional dumpsite during the study), rather than characterization by stratification. The dumpsite is about 20 km away from Ilorin city, along Ogbomosho -Ilorin express way. Sampling on the dumpsite was performed eight (8) times every month, as suggested by [11]; sixty (60) samples were considered altogether instead of 15 samples recommended for stratification study, as suggested by [12]. Samples collected, were mixed together on a mat, to give a cone-shape which was divided into four slices [13,14]. Two diagonally opposite slices out

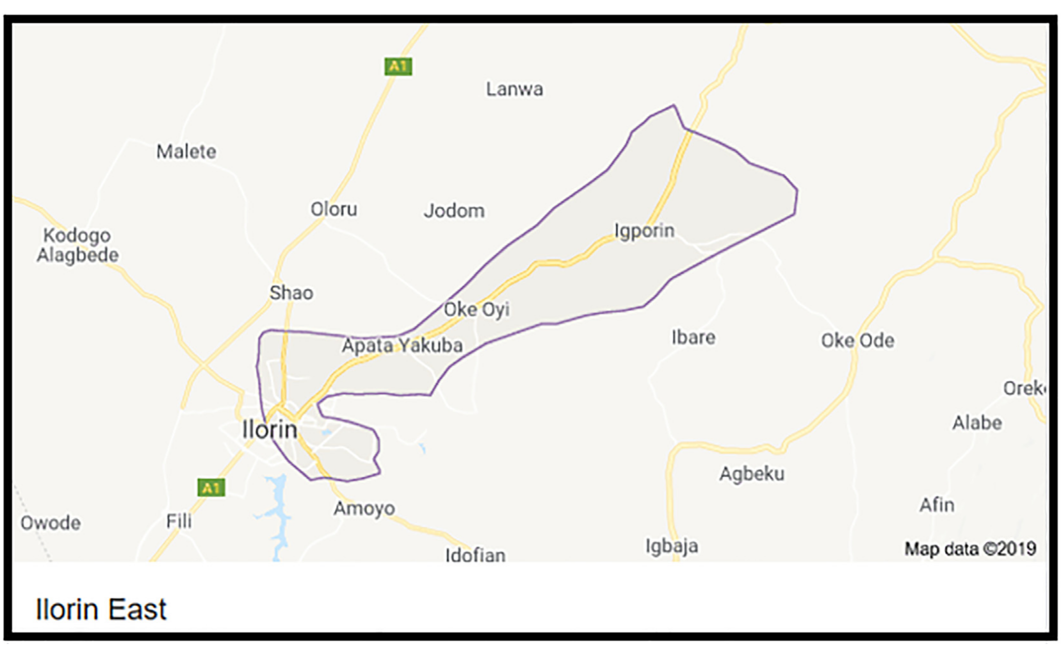

Fig. 1a. Map of Ilorin East showing the Towns therein (KMLS, 2009).

Fig. 1b. . Map of Ilorin West showing the Towns therein (KMLS, 2009).

of the four, were discarded and the remaining two were thoroughly mixed together again, to obtain 240 L of MSW as a reliable sample [12,11]. Thirty (30) samples each, were considered in every season to ensure adequate samples that will prevent errors resulting from insufficient samples, as suggested by [15]. The method used for the characterization was based on ASTM D5231 [16,11].

2.3. Physical analysis and characterization of waste samples

The physical characterization was performed by hand sorting the waste samples into respective fractions, on the (screening and sieving) table made of mild steel, of size, 1.5 m × 3.0 m with mesh surface of 10 mm × 10 mm shown in Plate 1 as adopted [5,11].

The batches of the waste samples were sorted into nineteen different fractions, kept in different receptacles, and their corresponding weight, volume, and hence the generation rate was determined and recorded. The nineteen waste components characterized, is presented in Tables 1(a and b)); nine combustible waste fractions out of the nineteen components were selected for energy projection; viz: food residue, paper, packaging-box, plastic bottle, polypropylene sack, grass/garden trimmings, textile (rags), nylon and wood as in Table 1(c).

2.4. Laboratory techniques

The nine (9) combustible MSW fractions selected for energy estimation, were shredded and milled individually into less than 2 mm, to permit easy digestion with reagents during laboratory tests [6,11]. Selection of the combustible waste fractions was because they occur regularly in the waste streams flows, which signifies sustainability and their combustibility characteristic. Each laboratory sample was prepared in triplicates for proximate analysis, using electric oven (DHG 9053 model) and electric furnace (TDW model) in Plates 2(a) and (b),

Fig. 1c. . Map of Ilorin South showing the Towns therein (KMLS, 2009.

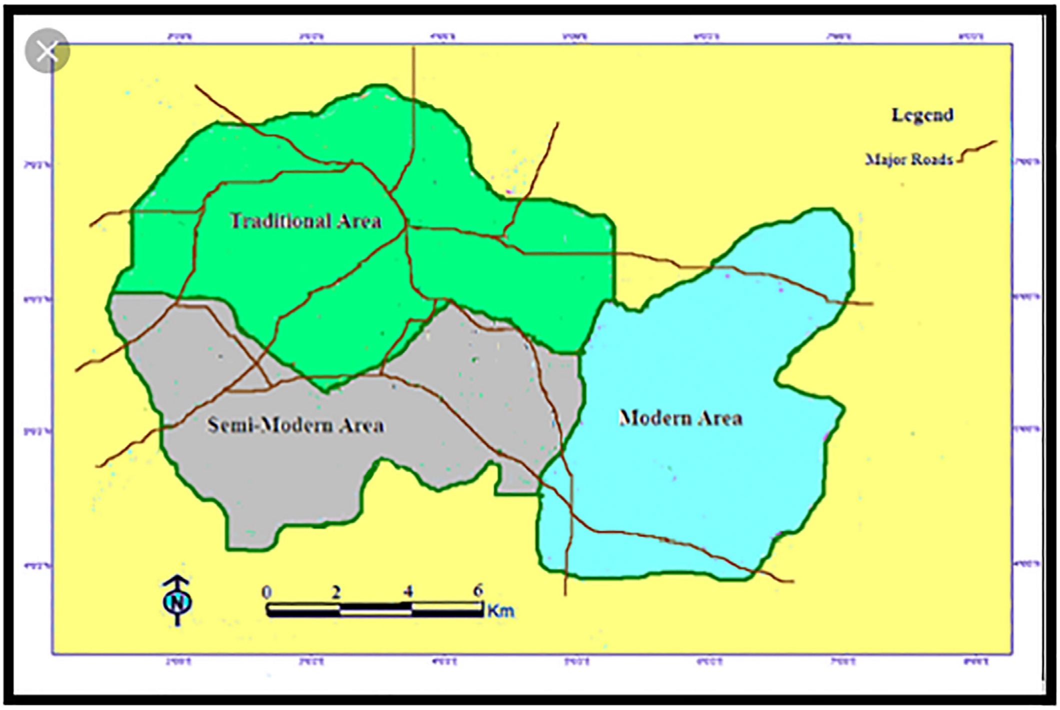

Fig. 2a. . Map of Ilorin Metropolis showing the Traditional, Semi-modern and Modern Areas (KMLS, 2009).

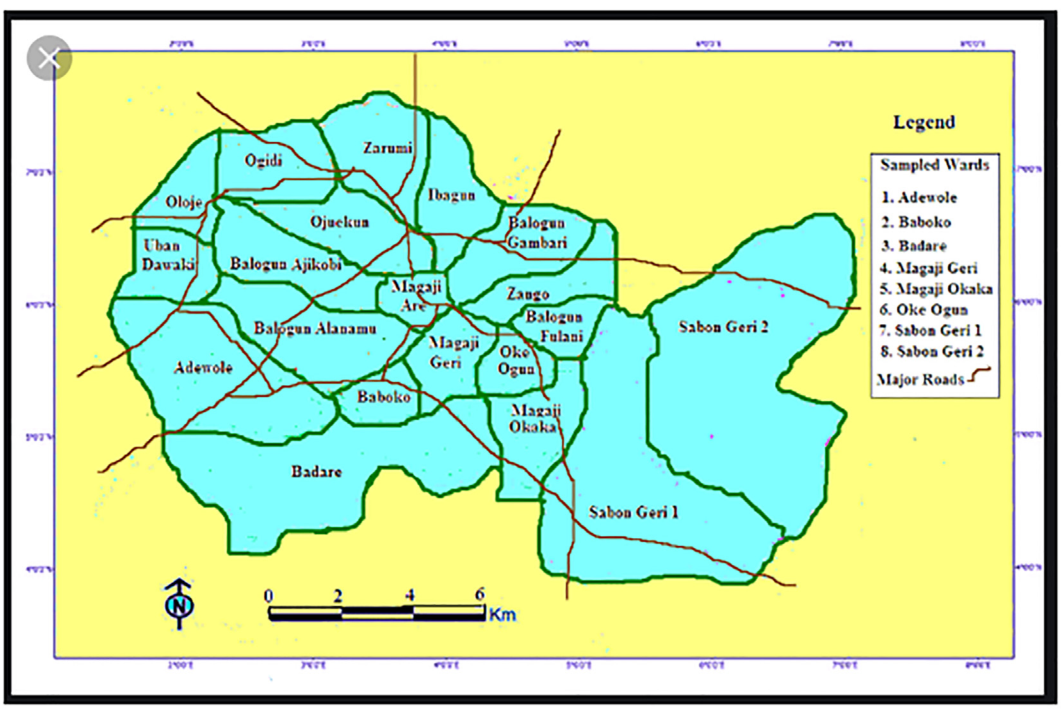

Fig. 2b. . The map of Ilorin showing some sampled political wards (KMLS, 2009).

respectively as suggested [5]. The Ultimate analysis was performed, using Elemental analyzer (Flash EA 1112 model), as suggested [4]. The heating value of each sample was determined using bomb calorimeter (e 2 k model) shown in Plate 3; as suggested [8].

2.4.1. *Determination of physicochemical characteristics*

Proximate analysis

Proximate analysis was performed to determine the moisture content, volatile matter, fixed carbon and the ash contents in each sample. Three (3) test samples of 1 g each, were measured into crucibles and dried in an Electric oven (DHG 9053 model), maintained at a temperature of 110° C for 1 h, based on ASTM D7582 – 12 Standard methods [6]. It was later removed and cooled in a desiccator. The loss in weight of the sample during drying is considered as its moisture content [17]. After determining the moisture content, the samples left in the crucible were weighed and heated using electric furnace (TDW model of 1200° C capacity) maintained at 950 °C for 7 min. The crucibles were withdrawn from the furnace and cooled in a desiccator, and

Table 1a
. Physical characterization of municipal solid waste streams during wet season.

Waste Fractions	MAY Wt. (kg)	JUN. Wt. (kg)	JULY Wt. (kg)	AUG. Wt. (kg)	TOTAL Wt. (kg)	VOL. m^3	Wt. %	kg/cap /day
Food residue	28.20	56.50	55.10	109.80	249.60	1.25	14.15	0.03
Wood	4.70	2.40	8.00	0.60	15.70	0.08	0.89	0.002
Paper	21.50	15.50	32.50	26.80	96.30	0.48	5.46	0.011
packaging box	56.80	47.50	50.00	63.00	217.30	1.09	12.32	0.025
Grass/trimmings	18.20	24.24	35.30	10.40	88.14	0.44	4.99	0.010
Texiles (rag)	21.60	27.40	21.50	60.40	130.90	0.65	7.42	0.015
Toiletries	33.70	22.80	25.60	15.60	97.70	0.49	5.54	0.011
Feaces	6.50	14.60	4.60	3.60	29.30	0.15	1.66	0.003
Cow dung	5.90	13.40	6.60	1.80	27.70	0.14	1.57	0.003
Nylon	58.40	66.80	41.10	47.40	213.70	1.07	12.11	0.024
Poly-sac	19.80	17.50	25.92	33.40	96.62	0.48	5.48	0.011
Plastic bottle	80.50	48.40	26.50	37.40	192.80	0.96	10.93	0.022
Rubber	0.80	1.00	0.80	1.00	3.60	0.02	0.20	0.000
Leather	0.00	1.00	0.00	0.40	1.40	0.01	0.08	0.000
Glass/Ceramics	7.90	9.60	9.60	8.60	35.70	0.18	2.02	0.004
Bones	7.60	8.60	3.20	2.20	21.60	0.11	1.22	0.003
Tins/Metals	45.20	15.20	22.10	6.80	89.30	0.45	5.06	0.010
Sand/Ash	12.45	14.60	11.20	6.40	44.65	0.22	2.53	0.005
Others	29.30	37.50	25.00	20.40	112.20	0.56	6.36	0.013
Grand Total	459.05	444.54	404.62	456.00	1764.21	8.83	100	0.201

Table 1b
. Physical characterization of municipal solid waste streams during dry season.

Waste Fractions	NOV. Wt. (kg)	DEC. Wt. (kg)	JAN. Wt. (kg)	FEB. Wt. (kg)	TOTAL Wt. (kg)	VOL. m^3	Wt. %	kg/cap/day
Food residue	3.70	46.30	10.90	8.00	68.90	0.34	5.27	0.008
Wood	1.60	3.40	4.00	0.00	9.00	0.05	0.69	0.001
Paper	14.80	31.50	30.50	12.60	89.40	0.45	6.83	0.009
packaging box	10.40	49.60	12.50	7.80	80.30	0.40	6.14	0.009
Grass/trimmings	31.60	8.20	6.90	2.40	49.10	0.25	3.75	0.006
Textile (rags)	27.20	46.00	42.40	27.30	142.90	0.71	10.93	0.019
Toiletries	18.40	14.10	29.10	31.10	92.70	0.46	7.09	0.010
Feaces	1.40	11.60	1.00	5.10	19.10	0.10	1.46	0.002
Cow dung	8.70	3.00	3.20	0.00	14.90	0.07	1.14	0.001
Nylon	59.00	70.40	72.20	52.50	254.10	1.27	19.43	0.028
poly-sac	23.20	11.30	24.20	8.20	66.90	0.33	5.11	0.008
Plastic bottle	7.00	64.20	18.40	18.30	107.90	0.54	8.25	0.012
Rubber	0.40	0.10	1.20	0.00	1.70	0.01	0.13	0.000
Leather	0.60	0.20	0.00	0.00	0.80	0.00	0.06	0.001
Glass/Ceramics	10.40	9.80	20.40	6.00	46.60	0.23	3.56	0.005
Bones	2.60	0.00	0.80	2.50	5.90	0.03	0.45	0.001
Tins/Metals	8.00	35.00	8.00	4.20	55.20	0.28	4.22	0.006
Sand/Ash	11.90	9.30	15.30	9.30	45.80	0.23	3.50	0.005
Others	20.00	50.60	59.40	26.80	156.80	0.78	11.99	0.018
Grand Total	260.90	464.60	360.40	222.10	1308.00	6.54	100.00	0.150

later weighed; the difference between the percentage loss in weight and the percentage moisture, is considered as the volatile matter [6,11]. Then, the residue left in the crucible, was heated without covering, inside the furnace kept at 700 °C for 30 min and was later cooled in the desiccator and weighed; the process was repeated to obtain a constant weight. The amount of residue obtained after ignition of solid waste, was considered as the ash content [6]. The fixed carbon content was determined based on ASTM D3172-73, by deducting the percentage of ash, moisture, and volatile matter from 100 [11].

Ultimate analysis

Table 1c
. The combustible MSW fractions considered for Energy production in the seasons.

Waste Components	WET SEASON				DRY SEASON				TOTAL
	MAY Wt. (kg)	JUN. Wt. (kg)	JULY Wt. (kg)	AUG. Wt. (kg)	NOV. Wt. (kg)	DEC. Wt. (kg)	JAN. Wt. (kg)	FEB. (kg)	Wt. (kg)
Food residue	28.20	56.50	55.10	109.80	3.70	46.30	10.90	8.00	318.50
Wood	4.70	2.40	8.00	0.60	1.60	3.40	4.00	0.00	24.70
Paper	21.50	15.50	32.50	26.80	14.80	31.50	30.50	12.60	185.70
packaging box	56.80	47.50	50.00	63.00	10.40	49.60	12.50	7.80	297.60
Grass/trimmings	18.20	24.24	35.30	10.40	31.60	8.20	6.90	2.40	137.24
Textiles (rag)	21.60	27.40	21.50	60.40	27.20	46.00	42.40	27.30	273.80
Nylon	58.40	66.80	41.10	47.40	59.00	70.40	72.20	52.50	467.80
poly (BAGCO sack)	19.80	17.50	25.92	33.40	23.20	11.30	24.20	8.20	163.52
Plastic bottle	80.50	48.40	26.50	37.40	7.00	64.20	18.40	18.30	300.70
TOTAL	309.70	306.24	295.92	389.20	178.50	330.90	222.00	137.10	2169.56

Ultimate analysis was performed to evaluate the total carbon (C), hydrogen (H), nitrogen (N), Sulphur (S), oxygen (O) percentage contents; after removal of volatile matters, moisture and ash contents based on ASTM D5291 using Flash EA 1112 Elemental analyzer [11]. About 0.5 g of each milled sample was weighed into a crucible for combustion. The flue produced was passed into a chromatography column to detect oxides of sulphur, nitrogen, hydrogen and carbon produced, using thermal conductivity detector (TCD) and '*Eager 300 software*' was used to analyze the electrical signals produced to reveal the percentage contents of sulphur, nitrogen, hydrogen and carbon, available in each sample. The average values of the results obtained in the replicated samples, are considered as the typical values [11].

The high heating value (HHV) of each sample for both wet and dry season characterization, was determined based on ASTM D5468-02, using e 2 k combustion calorimeter shown in Plate 3, according [18,6]. 0.5 g of each replicated sample was combusted in the bomb at high-pressure of oxygen-atmosphere. The result obtained was displayed on the screen of the connected computer, after completion. The average value of the results for the triplicate sample was considered as the 'typical' HHV (MJ/kg) of each component.

The HHV obtained from bomb calorimeter was inputted to the model in Eq. (1), to get the low heating value (LHV^1); [4]. The percentage contents of the chemical elements obtained from the ultimate analysis were inputted to the standard models of Dulong and Steuer in Eqs. (2) and (3), to obtain LHV^2 and LHV^3 respectively as suggested by [4]. The average of the heating values obtained from Eqs. (1) to (3), is considered as the typical low heating value, which is the appropriate heating value, used in estimating the energy potential of the MSW to be utilized as solid fuel.

$$LHV^1 = \sum_{1}^{9} W_j \times HV_j \tag{1}$$

From Eq. (1), $LHV^1$is the net low heating value, W_j is the percentage weight of each waste fraction and HV_j is the high heating value of each fraction from bomb calorimeter.

The low heating value, LHV^2 in Eq. (2), was calculated by adopting Dulong's model,

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

The low heating value, LHV^3in Eq. (3), was determined by adopting Steuer's model.

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

LHV^2andLHV^3 are the respective low heating values in Eqs. (2) and (3). Carbon (C), hydrogen (H), Sulphur (S), oxygen (O) and moisture (W) are the percentage constituents from ultimate analysis.

The average value of low heating value (LHV) obtained from Eqs. (1) to (3) is considered as the typical heating value used to calculate energy potential (EP_{msw}), in Eq. (4) and electrical power potential (EPP_{msw}), in Eq. (5) [4].

2.5. Estimation of energy potential (EP_{msw}) and electrical power potential (EPP_{msw})

$$EP_{msw} = LHV_{msw} \times w_{msw} \times \frac{1000}{3.6}(\text{kWh}) \tag{4}$$

EP_{msw}(kWh), is the energy potential of MSW; W_{msw} (tons), is the weight of MSW; LHV_{msw} (MJ/kg), is the net low heating value of the MSW obtained as average value from Eqs. (1)–(3). Conversion ratio (1kWh = 3.6 MJ).

$$EPP_{msw} = LHV_{msw} \times \frac{w_{msw}}{24} \times \frac{1000}{3.6} \times \int (\text{kW}) \tag{5}$$

$\int$ is the converting efficiency in a power plant, [19,4]. gives the conversion efficiency ($\int$) range to be 20–40%. The conversion efficiency of 30% is adopted.

2.6. Statistical modelling

Multiple regression analysis was performed using *Gnu* Regression, Econometrics and Time-series Library (GRETL) software to model the heating value of the MSW of both seasons. The energy content of MSW was determined based on ultimate analysis and proximate analysis of MSW [11,4]. Eight (8) models were developed in the analyses. Four models altogether, for the proximate and ultimate analyses of both wet and dry seasons, using ordinary least square estimator (OLS); also one model each for diagnosing the earlier models developed for both proximate and ultimate analyses, using ridge regression estimator [20] because OLS is only effective when certain assumptions are satisfied. Jarque-Bera test was conducted to determine if the error term in the model follows a normal distribution. The variance inflation factor (VIF) was also used to examine the correlation of regressors. The dependent variable in each model is the heating value (HV), and the independent variables are the physicochemical characteristics. The models can appropriately predict the impact of a change of any of the independent variables (proximate and ultimate characteristics), on the heating value and the energy potential of the MSW.

3. Results and discussion

3.1. Physical characterization

The results of analysis of MSW fractions during the rainy season in May to August 2016 is presented in Table 1(a). The weight of MSW samples characterized for wet season was about 1764 kg, with specific bin volume of 8.83 m^3. An aggregate of about 51,620 tons of MSW was generated during the span of the wet season of the year, with a generating rate of 0.20 kg/capita per day. The characterization shows that the waste produced in May was the highest with 26%, followed by that of August 25% and the least was the month of July with 23%. Table 1(b) shows the physical analysis of waste fractions generated during the dry season in November 2016 to February 2017. The quantity of waste characterized for the dry season was 1308 kg, with specific bin volume of 6.54 m^3. Also 38,712 tons of MSW was generated during the dry season of the year, with 0.15 kg/capita/person rate of generation.

The average waste generated in both seasons was 90,332 tons, compared to 250 tons in Ado-Ekiti [21], 30 million tons in US [22], 2.15 million tons in Sweden [23] and 46 million in China [24]. The combined rate of generation for both seasons was 0.35 kg/capita/person, compared to 0.09 kg/capita/day in Ghana, 2.00 kg/capita/day in South Africa, 1.34 kg/capita/day in United Kingdom and 2.13 kg/capita/day in United States [25]. The characterization for the dry season showed that December had the highest generated waste of 36%, followed by January 28% and the least in February with 17%; this could be as a result of more commodities of different kinds that were purchased during celebrations at the end of a year and the beginning of a new year.

The percentage compositions of the combustible waste fractions in the physical characterization of the waste streams for both seasons are presented in Tables 1(a and b). Table 1(a) reveals that the total quantity of municipal solid waste characterized during wet season is 1764.21 kg MSW and Table 1(b) presents characterization of 1308 kg MSW for the dry season; thereby making a total weight of 3072.21 kg MSW for the combined characterization of the seasons. Table 1(c) shows that 2169.56 kg of combustible municipal solid waste was characterized

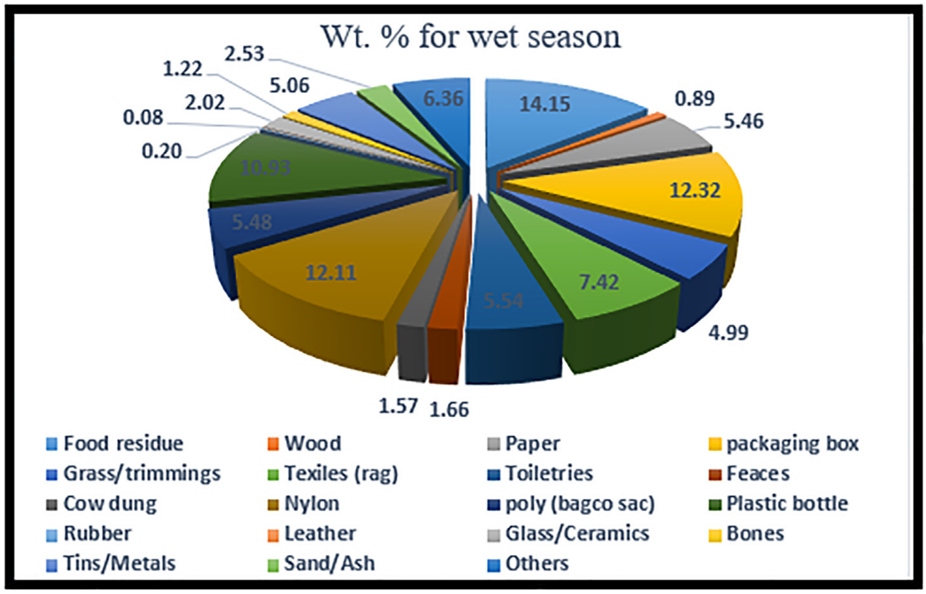

Fig. 3a. . Municipal solid waste (MSW) distribution during wet season.

during the two seasons, this implies that combustible waste fractions forms 70.62% of the total MSW components of the wastes generated in the two seasons (wet and dry).

3.1.1. MSW distribution at both the wet and dry seasons.

The MSW distribution for the wet season presented in Fig. 3(a), shows that food residue of 14.15% has the highest proportion, followed by packaging-box of 12.32%, and the least is leather of 0.08%. The reason for food residue being the highest fraction, could be because of the newly harvested food crops which makes food items available and affordable for people. Dry season MSW distribution shown in Fig. 3(b) reveals Nylon as the highest proportion with 19.43%, followed by others with 11.99%, and the least is leather with 0.06%. The reason for the highest fraction of nylon should be, because, people drink more water during the dry season, and most people prefer to go for sachet water packaged in nylon, because, it is affordable and readily available. It is a rare thing to come across leather waste in Ilorin because it is a valuable material, used in making bags, shoes and other ornamental materials in Ilorin.

3.2. Physicochemical characterization of wet and dry seasons wastes

The physicochemical characterization of MSW generated during the wet season is presented in Table 2(a). The proximate analysis reveals that fixed carbon (FC %), ranges from 12.50 to 96.56%; volatile matter (VM %) 2.44 ≤ 72.00%, moisture content 0.01 ≤ 14.10% and ash content (Ash %) 1.01 ≤ 23%. The ultimate analysis in Table 2(a), shows that carbon content ranges from 20.78 to 37.98%, hydrogen content 0.078 ≤ 0.164%, nitrogen content 2.685 ≤ 5.102%, Sulphur 0.049 ≤ 0.092%and oxygen content 0.063 ≤ 0.084%.

The physicochemical analysis of dry season MSW is presented in Table 2(b). The proximate analysis reveals that fixed carbon (FC %), ranges from 14 to 97%; volatile matter (VM %) 1.00 ≤ 66.00%, moisture content 0.00 ≤ 13.00% and ash content (Ash %) 1.00 ≤ 18.00%. The ultimate analysis in Table 2(b), shows that carbon content ranges from 21.07 ≤ 38.08%, hydrogen content 0.08 ≤ 0.17%,

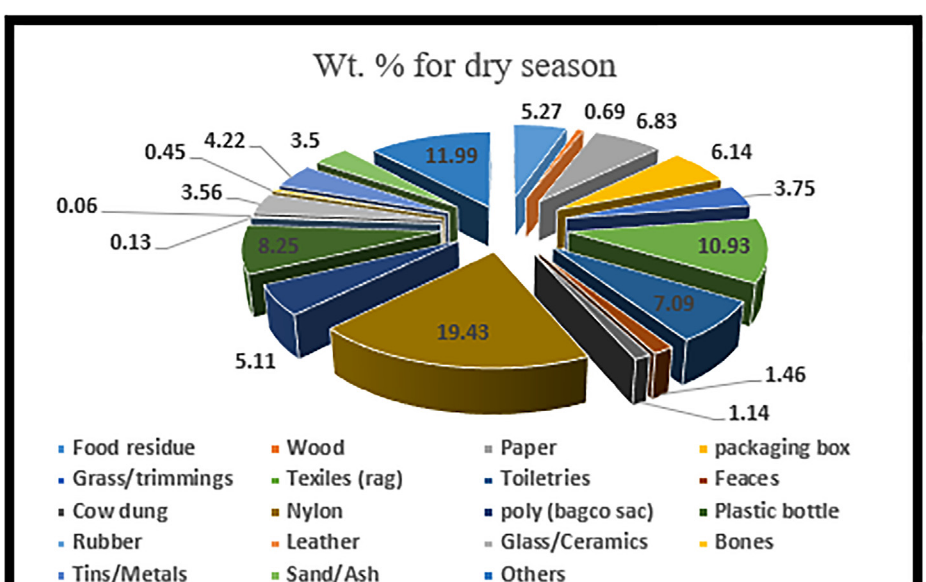

Fig. 3b. . Municipal solid waste (MSW) distribution during dry season.

Table 2a
. Physicochemical analysis of wet season municipal solid wastes.

Waste Fractions	Proximate Analysis				Ultimate Analysis				
Types	FC %	VM %	Ash%	M%	C %	H %	N %	S %	O%
Packaging Box	64.80	16.70	15.30	4.90	20.890	0.115	2.685	0.123	0.080
Water Nylon	84.33	19.00	1.80	0.01	21.970	0.108	2.798	0.051	0.084
Textiles (rag)	28.67	54.00	18.10	6.40	33.890	0.099	4.369	0.092	0.074
Paper Waste	23.11	59.00	10.40	7.90	35.360	0.142	5.102	0.079	0.068
Food waste	87.89	3.20	2.44	6.44	37.980	0.164	5.012	3.102	0.082
Polythene-sac	85.33	4.44	11.10	0.01	20.780	0.089	2.685	0.050	0.074
Wood	12.50	72.00	1.44	14.10	36.350	0.135	4.489	0.085	0.068
Grass/Trimmings	13.11	65.20	23.00	10.40	30.820	0.078	3.901	0.072	0.063
Plastic bottle	96.56	2.440	1.010	0.01	23.070	0.100	2.900	0.049	0.077

nitrogen content 2.69 ≤ 4.91%, Sulphur 0.05 ≤ 3.07%and oxygen content 0.06 ≤ 0.08%.

3.3. HV analysis of combustible waste fractions.

The HVs of both seasons were analyzed, using the three models in Eqs. (1)–(3); the average heating value got from the models is considered as a typical HV for each season. In Table 3, the energy characterization for the wet season MSW, reveals that the net low HV (i.e. typical heating value) of the season is 26 MJ/kg. The HV is about 130% of the energy in biomass wood, 88% of that of coal, 32% of that of uranium and 21% of that of hydrogen [26,4]. It is also rated to be 57% of the energy in petrol, 54% of that of natural gas, 52% of the energy in diesel, and 50% of the energy in methane [26,4]. Ditto the dry season energy characterization shows the typical HV of dry season wastes to be 29 MJ/kg. The dry season HV of 29 MJ/kg is about 152% of the energy content in biomass wood, 98% of that of coal, 36% of the energy in uranium and 24% of that of hydrogen [26,4]. It is also 64% of the energy in petrol, 60% of that of natural gas, 58% of the energy in diesel, and 55% of the energy in methane [26,4]. The average LHV of MSW for both seasons was 28 MJ/kg compared to 58 MJ.kg in Ado-Ekiti based on 52 MW of power from 253 tons of MSW [21], 117 MJ/kg of China based on 18.7 billion kWh of power from 46 million tons of MSW [24] and 134 MJ/kg in US based on 14 billion kWh of electricity from 30 million tons of MSW [22].

3.3.1. Heating value distribution of both seasons

In Table 3, the wet season heating value distribution is within the range of 0.22 to 7.61 MJ/kg. Nylon component had the highest heating value 7.61 MJ/kg, followed by plastic bottle 5.48 MJ/kg, and the least was wood with 0.22 MJ/kg while the dry season heating value distribution was in the range 0.19 to 13.56 MJ/kg. Nylon component has the highest heating value of 13.56 MJ/kg, followed by plastic bottle 4.60 MJ/kg, and the least is wood with 0.19 MJ/kg. The physicochemical analyses in Tables 2(a and b), show that Nylon and Plastic-bottle waste fractions, both have high fixed carbon and carbon contents, very low ash content and no moisture content at all, but Nylon had a little higher hydrogen, Sulphur and oxygen contents than plastic-bottle, and shows about twice the percentage weight of plastic-bottle, in the characterization Tables 1(a and b). This would have been responsible for its higher heating value than others. The wood component had the least percentage weight and volume, in the waste stream, low fixed carbon, and the highest moisture and volatile matter contents. This may be the reason for its low heating value.

3.4. Heat energy and electrical power potentials of the combustible waste fractions

The amount of waste generated during the wet season was about 210 tons/day, with a rate of 0.2 kg/capita/day; and that of the dry season was 158 tons with generating rate of 0.15 kg/capita/day. Seventy per cent (70%) of the waste generated in each season was considered for energy generation, using Eqs. (5) and (6). The heat energy and the electrical power potentials of the MSW generated in both seasons are presented in Table 4. The energy potential of the wet season wastes was calculated to be 1.1 GWh and its electrical power potential is 13.3 MW while the heat energy and electrical power potentials of the dry season MSW were estimated to be 890.2 MWh and 11.1 MW, respectively. The heat energy potential produced by the wet season wastes, is equivalent to energy potentials of 110,000 L of petrol; 99,308 L of diesel; 101,197 L of kerosene; while the energy potential of the dry season wastes, is equivalent to that of 91,772 L of petrol; 83,195 L of diesel; 89,198 L of biodiesel and 84,780 L of kerosene [27]. Ibadan Electricity Distribution Company (IBEDC) predicted for Kwara State to enjoy stable supply of electricity they need 270 MW power generation. It implies, that the energy potential estimated for the waste generated during wet-season will meet 5% of power demand in Kwara State, while the energy potential of dry-season wastes will provide 4.1% of the power demand in Kwara State using waste-to-energy (WTE) technology in Ilorin metropolis.

Table 2b
. Physicochemical analysis of dry season municipal solid wastes.

Combustible Waste fractions	Proximate Analysis				Ultimate Analysis				
	FC %	VM %	Ash %	M %	C %	H %	N %	S %	O %
Packaging Box	67.00	14.00	15.00	4.00	21.08	0.11	2.69	0.05	0.08
Water Nylon	85.00	14.00	1.00	0.00	22.18	0.11	2.83	0.06	0.09
Textiles (rag)	29.00	47.00	18.00	6.00	34.25	0.10	4.37	0.08	0.07
Paper Waste	28.00	55.00	10.00	7.00	35.41	0.09	4.52	0.08	0.07
Food waste	91.00	1.00	2.00	6.00	38.08	0.17	4.91	3.07	0.08
Polythene-sac	88.00	4.00	8.00	0.00	21.07	0.10	2.69	0.05	0.08
Wood	20.00	66.00	1.00	13.00	35.77	0.09	4.56	0.08	0.07
Grass/Trimmings	14.00	59.00	17.00	10.00	30.73	0.08	3.92	0.07	0.06
Plastic bottle	97.00	2.000	1.000	0.00	23.08	0.10	2.94	0.05	0.08

Table 3
. Physical and thermal analysis of wet and dry seasons' municipal solid wastes.

Waste Fractions	Dry-season Energy Characterization				Wet-season Energy Characterization			
	Total Wt. (kg)	Wt. %	Vol. m^3	LHV (MJ/kg)	TOTAL Wt. (kg)	Wt. %	Vol. m^3	LHV (MJ/kg)
Food residue	68.90	7.93	0.34	1.43	249.6	19.18	1.25	3.46
Wood	9.00	1.04	0.05	0.19	15.70	1.21	0.08	0.22
Paper	89.40	10.29	0.45	1.66	96.30	7.40	0.48	1.19
Packaging box	80.30	9.25	0.40	1.43	217.3	16.70	1.09	2.58
Grass/trimmings	49.10	5.65	0.25	1.00	88.14	6.77	0.44	1.20
Textile (rags)	142.9	16.45	0.71	2.29	130.9	10.06	0.65	1.40
Nylon	254.1	29.26	1.27	13.56	213.7	16.43	1,07	7.61
Polythene-sack	66.90	7.70	0.33	2.98	96.62	7.43	0.48	2.87
Plastic bottle	107.9	12.42	0.54	4.60	192.8	14.82	0.96	5.48
Grand Total	868.5	100	4.34	29.13	1301.1	100	6.51	26.02

Table 4
. Heat energy and power potentials analyses of the MSW for both seasons.

Combustible Waste Fractions	Energy and Power potentials of wet season MSW			Energy and Power potentials of dry season MSW		
	LHV MJ/kg	EPP_{MSW} (kW)		LHVMJ/kg		
Food residue	3.46	141,247	1766	1.43	43,708	546
Wood	0.22	9078	113	0.19	5834	73
Paper	1.19	48,638	608	1.66	50,618	633
packaging box	2.58	105,298	1316	1.43	43,620	545
Grass/ trimmings	1.20	49,108	614	1.00	30,668	383
Textiles (rag)	1.40	57,104	714	2.29	69,883	874
Nylon	7.61	310,795	3885	13.6	414,274	5178
Poly-sac	2.87	117,334	1467	2.98	91,074	1138
Plastic bottle	5.48	223,962	2800	4.60	140,508	1756
Grand Total	26.02	1,062,566	13,282	29.13	890,188	11,127

3.4.1. Modelling the energy content of MSW, using multiple regression analysis

Regression models developed in this study were obtained, using OLS, and ridge regression estimator fitted to variables derived from proximate and ultimate analyses, conducted on the combustible MSW fractions of both seasons. A diagnostic check was performed on the models to ascertain any tendency of multicollinearity. It was the multicollinearity result that necessitated the use of ridge regression estimator. The models developed in this study were used to predict the correlation between the energy content of municipal solid waste and its physicochemical characteristics.

3.4.2. Modelling the energy content of wet-season waste fractions, using proximate values

The correlation between the proximate analysis values and the heating (or calorific) value of the wet season wastes, presented in Table 5a, was obtained from multiple regression analysis by using OLS [6], and the model develop is shown in Eq. (6).

$$H\hat{V} = -28.89 + 0.3508FC + 0.3358VM + 0.1885Ash \quad (6)$$

Where, *HV* is the average heating value of the combustible waste fractions in wet season, *FC* is the average fixed carbon content of the waste components, *VM* is the average volatile matter content and *Ash* is the average ash content.

A diagnostic check on the model in Eq. (6), was performed and an examination on error term distribution was carried out, using the Jarque–Bera test. The statistic value was determined to be 2.22075 with a p-value of 0.3294. The result showed that the error term in Eq. (6) is normal. The constant error variance was also tested for, using white test, it was observed that there is constant variance; since, the white test p-value (0.15027) is > 0.05. VIF was used to ascertain if the independent variables (FC, VM, and Ash) are not related. It is conventionally acceptable, to say the independent variables are associated, if the VIF is higher than 10. The maximum VIF is higher than 10, which shows that the independent variables are related. However, there is a need for an alternative method to estimate the parameters in Eq. (6). OLS estimator suffers a breakdown when the independent variables are related [28]. An alternative estimator used, is ridge regression estimator as suggested by Lukman and Ayinde [29] and adopted by Ibikunle et al. [6]. The regression model generated when ridge regression was used is in Eq. (7).

$$H\hat{V} = -25.1476 + 0.3128FC + 0.2936VM + 0.1596Ash \quad (7)$$

where: *HV* is the heating value, *FC* is the fixed carbon content, *VM* is the volatile matter content and *Ash* is the ash content.

From the ridge regression estimate, *FC*, *VM* and *Ash* have a positive effect on the heating value. A unit increase in *FC* and *VM* contents, will increase the heating value of the waste by 31%, and 29% respectively, while a unit increase in and *Ash* content will reduce the heating value by 16%.

3.4.3. Modelling the energy content of wet-season waste fractions, using ultimate values

The modelling of the energy content of MSW fractions of wet season, with the corresponding ultimate values, is presented in Table 5b

Table 5a
Modelling the energy content for wet-season wastes using proximate values.

Ordinary Least Square Estimator and its Diagnostic check					Ridge Regression (Wet season)			
Regressors	Coeff.	SE	t-ratio	p-value	Regressors	Coeff.	SE	P-value
Constant	−28.89	7.0202	−4.12	0.0004 ***	constant	−25.1476	6.1090	0.0004
FC_	0.3508	0.0712	4.925	0.0001***	FC_	0.3128	0.0620	0.0000
VM_	0.3358	0.0796	4.220	0.0003***	VM_	0.2936	0.0694	0.0003
Ash_	0.1885	0.0632	2.982	0.0067***	Ash_	0.1594	0.0572	0.0105
R-squared	0.7041	F-testP-value	18.23992.79e-06					
Adjusted R-squared	0.6655	Jarq-Bera-tP-value	2.220750.3294					
MAX(VIF)	53.907	White testP-value	13. 28160.15027					

Table 5b
Modelling the Energy Content for wet-season wastes using Ultimate values.

Ordinary Least Square Estimator and its Diagnostic check					Ridge Regression (Wet season)			
Regressors	Coeff.	SE	t-ratio	p-value	Regressors	Coeff.	SE	P-value
Constant	−11.07	10.2653	−1.078	0.2931	constant	9.870	2.356	0.0004
C_	−0.005	0.3818	−0.013	0.9902	C_	−0.292	0.343	0.4035
H_	−5.507	25.1935	−0.218	0.8291	H_	−0.151	11.73	0.9899
N_	−0.747	2.7892	−0.268	0.7915	N_	0.116	2.661	0.9658
S_	0.1924	0.8422	0.228	0.8215	S_	1.148	0.538	0.0450
O_	237.59	102.3560	2.321	0.0304	O_	12.96	5.159	0.0203
R-squared	0.5415	F-test	4.960					
		P-value	0.004					
Adjusted R-squared	0.4323	J-Bera- t	3.726					
		P-value	0.155					
MAX(VIF)	42.675	White test	14.37					
		P-value	0.811					

and the model developed is given in Eq. (8):

$$\widehat{HV} = -11.0699 - 0.0048C - 5.5074H - 0.7469N + 0.1924S + 237.59O \quad (8)$$

Where, HV is the average heating value of the combustible fractions, C is the average carbon content of the combustible fractions, H is the average hydrogen content of the combustible fractions, S is the average Sulphur content and O is the average oxygen content.

The regression model for the ultimate analysis in wet season is obtained using OLS [6]. Having diagnosed Eq. (8) with the Jarque–Bera test, the error term was found to be normally distributed. The statistic value is 3.7264 with a p-value of 0.1552 which exceeds 0.05. The result shows that the error term in Eq. (8), is normal. The white test is used to check if there is constant error variance. The p-value of the white test is 0.8111 which is greater than 0.05. VIF was used to examine if the regressors are related. The regressors are related since VIF is greater than 10. Lukman and Arolowo [28], reported that OLS estimator suffers a breakdown when the independent variables are related; and Lukman and Ayinde [29] reported that regression coefficient can possess a wrong sign when the independent variables are related. An alternative estimator used is the ridge regression estimator adopted by [4]. The regression model developed using ridge regression is in Eq. (9):

$$\widehat{HV} = 9.8701 - 0.2921C - 0.1510H + 0.1155N + 1.1478S + 12.959 \quad (9)$$

The estimation obtained from the ridge regression, reveals that: Nitrogen, Sulphur and Oxygen all have a positive impact on energy potential, while Carbon and Hydrogen have a negative effect. A 1% increase in Carbon, Nitrogen, Sulphur and Oxygen will increase the heating value by 29, 12, 115 and 1296% respectively; while 1% increase in Hydrogen will reduce the heating value by 15%.

3.4.4. Modelling the energy content of dry-season waste fractions, using proximate values.

The energy content was modelled with the HV of MSW as a dependent variable, and the physicochemical characteristics of proximate analysis as independent variables. The details of the modelling analysis are presented in Table 6a and the model developed is in Eq. (10).

$$\widehat{HV} = -31.689 + 0.37705FC + 0.36373VM + 0.31286Ash \quad (10)$$

where: HV is the average heating value of the combined combustibles, FC is the average fixed carbon content of the combustibles, VM is the average volatile matter content and Ash is the average ash content of the combustibles.

We checked if the error term in model Eq. (10) is normally distributed using the Jarque-Bera test; and found the statistic value to be 3.25356 with p-value of 0.1966. The error term is normal since p-value exceeds 0.05. The constant error variance was determined using the White test. A constant variance was noticed since the p-value (0.4476) of the white test was greater than 0.05. The maximum VIF is higher than 10, which shows that the independent variables are related. Moreover, an alternative estimator (the ridge regression estimator) is used, because of the breakdown suffered by OLS estimator due to related independent variables.

The regression model using ridge regression is stated in Eq. (11).

$$\widehat{HV} = -23.5839 + 0.2952FC + 0.2724VM + 0.2244As \quad (11)$$

From the ridge regression estimate, FC, VM, and Ash all have a positive effect on HV. In the absence of all these factors, the HV will reduce by about 24%. A unit increase in FC will increase HV by about 30% when other factors remain constant. A unit increase in VM will increase heating value by about 27% when other factors remain constant. A unit increase in Ash will reduce the HV by about 22% when other factors remain constant. The R-squared shows about 57% variation in the response expressed by the regressors. The F test shows that the overall model fitted to the data is significant at 5%.

3.4.5. Modelling the energy content of dry-season waste fractions, using ultimate values

The multiple regression model developed using ultimate values of wet-season wastes shows the correlation between the low HV of the MSW, and the chemical characteristics of the MSW obtained from ultimate analysis (i.e. C, H, N, and S) as presented in Table 6b. The model for the ultimate analysis in dry season presented in Eq. (12), is obtained using OLS method.

$$\widehat{HV} = -36.8688 + 0.444369C + 0.002761H - 2.96085N - 2.18059S + 530.5O \quad (12)$$

where HV is the average heating value of the combustibles, C is the average carbon percentage content of the combustible waste fractions, H is the average percentage hydrogen content of the combustibles, N is the average nitrogen percentage content and S is the average Sulphur percentage content of the combustibles.

The statistic value is 3.45659 with a p-value of 0.17758. The result shows that the error term in Eq. (12) is normal. The white test is used to test for constant error variance, it is observed from that there is constant variance since the white test p-value (0.31229) is higher than 0.05. The independent variables are associated because the VIF is higher than 10. Nevertheless, an alternative estimator (the ridge regression estimator), is used, because OLS estimator suffers a breakdown when the independent variables are related.

The regression model obtained using ridge regression is presented in Eq. (13):

$$\widehat{HV} = 10.8944 - 0.2296C + 4.7216H - 0.834N + 0.1150S + 28.006O \quad (13)$$

Carbon, Sulphur, Nitrogen and Oxygen all have a positive effect on

Table 6a
Modelling the energy content for dry-season wastes using proximate values.

Ordinary Least Square Estimator and its Diagnostic check					Ridge Regression (Wet season)			
Regressors	Coeff.	SE	t-ratio	p-value	Regressors	Coeff.	SE	P-value
constant	−31.689	12.8749	−2.4613	0.0217**	constant	–23.584	9.582	0.0218
FC_	0.3771	0.13023	28,954	0.0082**	FC_	0.2952	0.097	0.0058
VM_	0.3637	0.14568	24,967	0.0201**	VM_	0.2724	0.109	0.0198
Ash_	0.3128	0.14668	21,329	0.0438**	Ash_	0.2244	0.113	0.0585
R-square	0.5679	F-test	10.079					
		P-value	(0.0002)					
MAX (VIF)	116.45	White test	17.2625					
		P-value	(0.4476)					
Adjusted R-squared	0.5116	J-Bera-t	3.2536					
		P-value	(0.1966)					

heating value while Hydrogen has a negative effect. A unit increase in Carbon, Sulphur, Nitrogen and oxygen will increase the heating value by 23, 12, 83 and 28%, respectively; while a unit increase in Hydrogen will reduce the heating value by 472%.

4. Conclusion

From this study, 210 tons/day and 158 tons/day MSW, were produced during wet and dry seasons respectively. Out of 3072.21 kg MSW that was generated in both seasons, 70% of the aggregate MSW is combustible; that is, by adopting incineration method of waste management for energy recovery, only 30% of the MSW generated would be collected for disposal. Models developed revealed that 1% increase in fixed carbon and volatile matter, increases HV by ≥30% and ≥27% respectively. Also, 1% increase in nitrogen, Sulphur and oxygen contents raised HV by ≥12%, ≥ 15% and ≥13% correspondingly. The energy and power potentials for wet and dry seasons are, 1.1 GWh and 13.3 MW; 890.2 MWh and 11.1 MW respectively. The energy potential of the wet and dry seasons can cater for about 9.1% of power demand in Kwara State.

5. Recommendation

WTE via incineration is recommended as the best option of MSW management method for Ilorin, because the percentage of the combustible waste fractions to the aggregate of waste generated is about 71%, with HV ≥26 MJ/kg and generation rate of ≥0.15 kg/capita/person. This implies reduction in waste disposal at dumpsite by ≥70%, efficient waste management via energy recovery using MSW as a resource. It will also encourage reuse, recycling and energy recovery from waste fractions. Nevertheless, the wastes must be treated before conversion; to reduce pollutant precursors that include metals, nitrogen and other elements. The incinerating plant should be installed in a controlled environment, also the technology should contain electrostatic precipitator and absorbents (like lime and activated carbon), to control emission of particles and flues. Moreover, the models developed on the physicochemical properties of the waste fractions shows that a unit increase in Hydrogen and Ash contents will reduce the HV correspondingly with ≥15% and ≥16%. Therefore, there is a need to pretreat the waste fractions to minimize the adverse effects of hydrogen and ash contents on the HV before using the MSW as an energy resource.

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CRediT authorship contribution statement

R.A. Ibikunle: Conceptualization, Investigation, Methodology, Resources, Writing - original draft, Writing - review & editing. **I.F. Titiladunayo:** Project administration, Supervision. **A.F. Lukman:** Data curation, Formal analysis, Software. **S.O. Dahunsi:** Project administration, Investigation, Funding acquisition. **E.A. Akeju:** Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 6b
Modelling the energy content for dry-season combustible fractions using ultimate values.

Ordinary Least Square Estimator and its Diagnostic check					Ridge Regression (Dry season)			
Regressors	Coeff.	SE	t-ratio	P-value	Regressors	Coeff.	SE	P-value
constant	−36.868	19.2265	−1.9176	0.06886*	constant	10.8944	4.4133	0.0222
C_	0.444	0.71517	0.6213	0.54106	C_	−0.2296	0.6416	0.7241
H_	0.003	47.1864	0.0001	0.99995	H_	4.7216	21.9675	0.8319
N_	−2.961	5.22405	−0.5668	0.57688	N_	−0.834	4.9831	0.8687
S_	−2.181	1.57732	−1.3825	0.18136	S_	0.1150	1.0084	0.9103
O_	530.5	191.709	2.7672	0.01155**	O_	28.006	9.6636	0.0086
R-squared	0.455	F-test	3.5004					
		P-value	0.0185					
Adjusted R-squared	0.325	White test	22.533					
		P-value	0.3122					
MAX(VIF)	42.67	J-Bera-t	3.4565					
		P-value	0.1775					

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2020.118122.

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