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# ANALYSIS OF COMBUSTIBLE MUNICIPAL SOLID WASTE FRACTIONS AS FUEL FOR ENERGY PRODUCTION: EXPLORING ITS PHYSICO-CHEMICAL AND THERMAL CHARACTERISTICS

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## ABSTRACT

*An investigation study on municipal solid waste generation and physicochemical characteristics of combustible fractions was carried out in Ilorin metropolis. This was driven by a need to meet energy demand and reduce the consequential effects of wastes for clean and green habits. Ilorin waste sector, requires detailed information on the physicochemical characteristics of the wastes fractions, to choose the appropriate method for waste management in the city. A240 litres bin volume of wastes was sampled 62 times within eight months at Lasoju dump-site. The conformity of the combustible wastes with the characteristics required of solid fuel was investigated. Manual sorting enables access to vital information about recovery and characteristics of waste components. Nine out of nineteen components characterized, were selected for Laboratory analyses. The results of the physical characterization, shows that 70% MSW generated is combustible. The proximate analysis reveals that the wastes contain more than 64% fixed carbon, 33 % volatile matter and 5 % of moisture content, while the ultimate analysis shows more than 29 % of carbon which can contribute to the calorific value of the MSW. Nitrogen is about 2.8 % and Sulphur about 0.2 %; the small average amount of Nitrogen and sulphur present, will cause reduction of emissions during combustion. The energy content of the MSW determined, using bomb calorimeter was about 20 MJ/kg. The results show that the MSW stream in Ilorin metropolis would serve as a reliable and sustainable renewable energy resource via combustion method.*

**Keywords:** Characterization, Combustible fractions, Municipal solid waste, Physicochemical properties

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# 1. INTRODUCTION

Municipal Solid Waste (MSW) management in Ilorin metropolis has become a concern as the generation rate increases on daily basis due to demographic growth, urbanization, change in consumption habits and patterns of the society. The waste management system of the city is insufficient and inefficient because of inadequate equipment, manpower and required technology to take proper care of the waste generated in the metropolis. This is evident by some uncollected MSW littering the surroundings of the collection centres as shown in Plate 1. In most cities of developing nations, waste disposal as a management function has its' shortcomings [1], particularly in Ilorin, due to negligence by the municipalities, lack of modern equipment and the required professionals. The MSW disposal methods practiced in Ilorin metropolis include the use of open dump, storage container and dumpsite and eventual disposal to the dump-site.

**Plate 1** The uncollected MSW dumped out of collection bin.

Open dump disposal method though an improper and illegal method, was noticed during the field work of this study. This uncultured practice was found every day in places ranging from the roads, walkways, vacant plots, water ways and streets of the city; shown in Plates 1 to 4.This can easily expose the public to health hazards caused by pollution, diseases' causative agents that breed on the waste dumps. The uncultured and indiscriminate disposal of MSW components is due to insufficient waste management system. Refuses dumped round the storage bins provided in some streets because it is a common practice to throw waste at random by the roads instead of the inside of the container. There are piles of uncollected MSW left in the streets, wastes dumped into the water courses and the blocking of drainage channels. The uncontrolled waste disposal can threaten urban surface water resources and pose significant environmental health risks to the residents leaving nearby to it [2],

**Plate 2** Piles of MSW deposited on the road divider along Emir's Road

**Plate 3** Illegal/Indiscriminate dump of MSW by the road side

**Plate 4** Illegal/Indiscriminate disposal of MSW into the waterways

The quantity of municipal solid waste (MSW) generated on daily basis are increasing [3]tremendously, the traditional method of waste disposal using landfill method, poses many problems, which include and degradation, surface water pollution and the emission of greenhouse gases (GHG) [4]. MSW management via incineration has advantages of waste volume reduction and energy recovery [5]. The need for characterization of MSW is to identify the various components in the wastes streams and to know the type of treatment required to enable energy recovery from waste fractions via combustion. Characterization of MSW is essential in the design and operations of incinerators. In this study, the nineteen available waste fractions of the city are physically characterized and only the nine combustible fractions namely: Food residue, Wood, Packaging box, Paper, Grass/garden trimmings, Textiles (rags), Nylon, Polythene sac and Plastic bottle were subjected to laboratory tests for physicochemical and heating value analysis.To have an efficient, reliable and sustainable municipal solid waste management system, the relevant stakeholders, i.e. the municipalities, non-governmental environmental agencies, waste sectors and the energy sectors; need to know the components and the physicochemical properties of the wastes streams they want to handle. It is then they will be able to identify the appropriate method of management system, mechanisms, the scientific treatment needed and the health protection equipment required. The aim of this study is to generate necessary scientific information on the physical, chemical, and heating properties of the combustible waste fractions which the waste management system can adopt as a management tool in taking decisions that affect waste disposal method, processing and energy recovery.

# 2. LITERATURE REVIEW

## 2.1. The Study Area

The Ilorin metropolis functions as the capital city of Kwara State and as the headquarters of three Local Government Areas viz: Ilorin West, Ilorin East and Ilorin South. Ilorin is selected for this study because, of its demographic growth and characteristic daily growth in waste generation. The population data collected form National Population Commission (NPC) Ilorin office, reveals the population census of Ilorin metropolis in 2006 to be 781934 with the following demographic breakdown: Ilorin East 207462, Ilorin South 209251 and Ilorin West 36522. In 2011 the population of the city was projected to be 908490 with the breakdown: Ilorin East 241040, Ilorin West 424330 and Ilorin South 243120. Ajadi and Tunde [6], stated that the city can be located on latitude 8°30'N and longitude 4°35'E with an area of about 100km$^2$. The geological settings of the city is of Pre-Cambian basement with an elevation of about 273m to 333m above sea level. The soil of the city is ferruginous in nature on crystalline acidic rock. The major river in the city (Asa River) covers a wide valley, and it divides Ilorin into two major parts: the eastern and the western part. The eastern part covers the GRA environment and the western part circumferences the core indigenous area. The vegetation is characterized with trees which include: Locust beans trees Acacia trees, Baobab trees and Shear-butter trees. The city has a tropical continental climate with high temperature round the year. The climate is made of wet and dry seasons. The wet season exists from the third month of the year to the tenth month (i.e. March to October), and the dry season is from the eleventh month to the second month of the following year (i.e. November to February). Ilorin being a traditional settlement, consists of characteristic traditional towns and villages alongside a modern urban centre. The traditional section covers the indigenous settlement located at west of Asa river with a concentric pattern. The modern urban centre includes the Emir's palace, Central mosque and Emir's market. There is also a commuter zone that consists of hamlets. Villages and towns where the weather city dwellers inhabit (e.g. Tanke, Ganmo). There are about 120 storage bins otherwise called Roro-bins located in some strategic collection centres in the city by Kwara State Environmental Protection Agency (KWEPA) as shown in Plate 1.

## 2.2. MSW generation and composition

MSW generation refers to the quantity of material that enters the waste stream before recycling, reuse, recovery, composting, or combustion. MSW generation has increased globally because of demographic and industrial growth, change in fashions and tastes, increase in family income and level of education. Other factors include: the seasons of the year, living arrangement, the framework of waste collection and its frequency, consumption pattern, and socioeconomic practices. In the economic factor, MSW generation is influence dby per capita income. The higher the economic status, the larger the volume of MSW generated. The composition of MSW corresponds to the factors responsible for the waste generation growth rate and is dynamic. In the developing nations of the globe, organic components of MSW are more predominant [7]. Economic status is one of the determinants responsible for the quantity of solid waste generated in a particular metropolis. Shekdar [8] expressed that lower amount of MSW are generated by the nations with lower GDP. The characteristics of municipal solid waste streams depends on their sources and seasons of MSW generation will determine the types of wastes, as well as rate of generation and composition. The accurate information on MSW characterization is essential for monitoring and regulating the existing MSW management systems for important management decisions.MSW could be characterized into various types viz: household wastes, garbage, ashes, rubbish, bulky wastes, Street wastes, animal wastes, and wastes from markets and business centres [9].

The types of wastes generated, depend on the kind of exercises, materials and the environment concerned in the generation. Poorer households, with lower level of income generate more organic food wastes. Waste composition in China was dominated by a high organic and moisture content, since the concentration of the kitchen waste in urban solid waste makes up the highest proportion at approximate 60% [10]. In industrialized countries', recyclables and lower bio-degradable organic wastes are generated. The high ratio of organic waste in China is attributed to the diet of more fresh vegetables and fruit compared to Western culture that has preference for food that is processed and packaged. The components of MSW in China is coal ash, which originates from household furnaces, because coal and wood are used for heating in the northern part of China and for cooking in major parts of the rural areas. On the average, 1.2 kg per capita of household solid waste is generated in the city of London per day. The estimated daily municipal waste generation rate in Kumasi is 0.6 kg per capita. In the year 2006, a total of 267,000 tonnes of both residential (58%) and non-residential (42%) waste was managed in the city of London as against 365,000 tonnes generated in Kumasi. It is estimated that households generate the highest amount of waste in Kumasi, followed by Markets, then industries with the least from institutions although the exact proportions could not be provided. The waste generation rate in the municipality is expected to increase by15% by the year 2010 [11]. Although the per capita waste generation in Kumasi is lower than that of the city of London the large population in Kumasi makes the overall waste generated in Kumasi higher than that of London [12].

The differences in waste composition may be attributed to the differences in the living standard and lifestyle of the inhabitants of the two cities. The abundance and type of the natural resources found in the countries of the two cities may also reflect in differences in the waste composition. According to Ajadi and Tunde [6], certain distinctions and likenesses exist in municipal solid waste generation and pattern of composition in Ilorin city, particular variation are shown in accessibility of dumpsters according to neighborhoods in Ilorin. In the old residential areas, such as Magaji-Ngeri, food wastes, bones, polythene bags, rags, leathers, rubbers and aluminum form the largest solid waste components that are generated there. Food waste is about 28%of the wastes generated, while other wastes mentioned takes about 21%. Paper waste and nylon constitute about 27.3%, leaves and human excrement (feaces) constitute 11.50% while non-organic wastes like bottle and tins constitute about 11.5% of the aggregate wastes generated. Taking after this is the new residential location, Oko-Erin ward. Paper wastes have the largest proportion amounted to 27.8% of the aggregate solid waste. Followed by this is food wastes with 25% and leaves and nylon components amount to 26.1%. The components characterized as others, constitutes 15.6% while tins and bottles constitute a minute proportion. Leaves and human excrement are 24.1% and 6.5% separately. In the Government Reservation Area (GRA), food wastes constitute 30.9% of aggregate waste; followed by paper waste with 23.0%. The wastes classified as others constituting 16.0% while leaves; nylon and tins/bottles constitutes 15% and 14.01% respectively. The data of the solid analyzed shows that food and paper wastes have a high percentage of the wastes generated. Because of food wastes from preparation processes, left over after consumption, all these contribute to a high rate of food wastes. Paper wastes, polythene sacks, metals, rubber among other wastes are generated by all independent of age or status in view of their various uses, for example, writing, packages, structures among others.

The high waste rate from food created by the GRA can be compared to the socio-economic attributes and household factor in the area. About 75% of the inhabitants in the GRA are high wage workers. This is high when comparing the old residential area to the new residential location; 27.1% and 52.0% of the general population falling into high pay. Both the G.R.A. and Old Residential Area display comparative pattern in family unit (household) estimate, as the rate of food waste is wide in the two zones. In the G.R.A, we have the largest constituents of tins/containers waste. This is in support of Awomuti [13], that rate of waste created in Residential and Commercial (market) land utilization is higher than the other land utilize regions. Moreover, the socio-economic attributes of the inhabitants of this region can likewise be utilized to clarify this. The high status of the inhabitants make it very feasible for them to have the capacity to consume more of items such as canned and bottled food drinks. Essentially, variations are noticed in other components. A few factors considered as reasons for variations in waste streams generated include: variation in climate at seasons; which affects the production of vegetables, fruits and other food items like corn, mangoes refuse, oranges among others which are regular in nature and thusly, a greater amount of them would be produced in wet seasons.

## 3. METHODOLOGY

This study estimated the MSW generation rate in Ilorin, the physicochemical and heating characteristics of combustible waste fractions in Ilorin metropolis. The graphical illustration of the methodology procedure is shown in Fig 1.

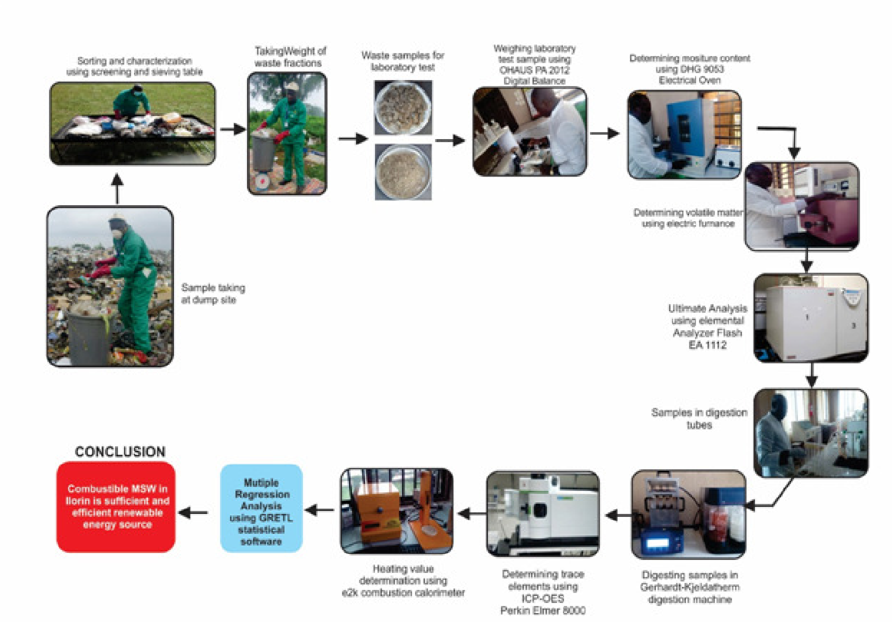


**Figure 1** Graphical Illustration of the methodology procedure

## 3.1. Materials and Method

According to properties of material, the MSW streams of Ilorin are categorized into food waste, wood waste, paper waste, packaging box (carton), grass/garden trimmings, textiles (rag), toiletries (sanitary pad, toilet tissue and pampers), feaces, cow-dung, nylon, polythene (bag co-sac), plastic bottle, rubber, leather, glass/ceramics, bones, tins/metals, sand/ash and others. The MSW fractions are generated from different places like households, market centres, institutions, business centres, event centres, parks and yards; but excluding hospital wastes and industrial wastes. Samples representing the total MSW generated in Ilorin metropolis were randomly collected from Lasoju dump site. The methodology involves sampling, sorting and characterization and laboratory analysis. In this study, a specific waste bin volume of 240 litres each, was taken in sixty – two (62) batches eight months; and were characterized. The combustible waste fractions selected for Laboratory tests include: Food waste, Wood, Paper waste, Packaging-box (carton), Grass/garden trimmings, Textiles (rag), Nylon, Polythene-sac, Plastic bottle. The physicochemical and the heating values of the combustible waste fractions were determined through Laboratory tests.

## 3.2. Sampling

Random sampling method suggested by Abdellah [14]was utilized to collect samples directly from Lasoju/Eyenkorin dumpsite during this study. Sixty-two (62) samples of 240 litres specific binvolume of MSW were collected. Samples were collected twice in a week (Tuesdays and Saturdays) for the eight months. A larger random subsets of a sample more than a sample was collected, and were poured on a large mat made of polythene sac material. It was properly mixed together with the aid of shovel, heaped together to form a cone shape, and later divided into four (4) slices [15][16]. Two diagonally opposite slices were discarded and the other two parts of the sample were thoroughly mixed together to obtain a representative sample of a specific waste bin volume of MSW of 240 litres for a batch (EC SWA-Tool, 2004).The sample taken was considered as the representation of the waste parent population. Thismethod of sampling was based on ASTM D5231 namely- random truck sampling and quartering [17][18].

## 3.3. Physical Characterization

Characterization of the waste was carried out based on the American Society for Testing and Materials (ASTM D5231). Each sample of 240 litres MSW collected was poured into a screening equipment, 1.5m x 3 m with 10 mm x 10mm mesh surface size designed for heterogeneous solid waste as recommended by WHO (1988) and adopted by [1]. The waste samples were sifted through the screen mesh to get rid of the sand and ash content which are inert compositions of the MSW in the combustion process. Then, the components remaining on the screening table, were manually sorted into different waste fractions, kept in different marked receptacles. Then the different waste fractions were characterized according to their weights, percentage composition, volume and generation rate in kg/capita/day as presented in Table 1.

## 3.4. Physicochemical Characterization

In this study physicochemical analyses refer to three measurements namely: proximate, ultimate and trace elements analyses. Each sample of combustible waste fraction was first shredded into smaller pieces and further milled to less than 1 mm using grinding machine. This was done to increase the surface area of the samples and to allow easy digestion during laboratory analyses. The proximate analysis was carried out using ASTM D7582 – 12 Standard methods. The moisture content was determined by oven drying 1gm of each sample in a crucible using electric oven (DHG 9053, 200 $^{o}$C capacity) maintained at about 110 °C for about 1 h. The loss in weight after cooling in a desiccator is reported as moisture content, using Equation 1according to [19][20].

$$M_{wet} = \frac{(w-d)}{w} \times 1001$$

Where$M_{wet}$ is the wet moisture content %, $w$ is the initial mass of sample as delivered (kg), and $d$ is the mass (kg) of the sample after oven drying.

The dried sample left in the crucible during after moisture analysis, was covered with a lid in a crucible and heated in an electric furnace (TDW, 1200 $^{o}$C capacity) maintained at 950°C for about 7 min, and was later cooled in a desiccator. The loss in weight is reported as volatile matter in percentage terms according to [21] and [20]using Equation 2:

$$V_d = \frac{A}{B} \times 100 \qquad 2$$

Where $V_d$ is the percentage volatile matter, $A$ is the mass loss of the sample, and $B$ is the mass of the sample taken.

The residue left after volatile matter analysis was heated without the lid inside the furnace at 700 °c for 30 min. The crucible was later cooled in the desiccator and weighed; heating and cooling processes was repeated to obtain a constant weight. The amount of residue obtained after ignition of solid waste, was considered as the ash content according to [19] and [22], using Equation 3:

$$Ash\ (\%) = \frac{w}{W} \times 100 \qquad 3$$

Where $w$,is the mass of ash and $W$ is the mass of the sample taken.

The fixed amount of carbon left behind was calculated according to ASTM D3172-73 [23] by deducting the percentage amount of ash, moisture, and volatile matter from 100, using Equation 4:

Fixed carbon (%) = 100 - (Moisture + Volatile matter + Ash). 4

The Ultimate analysis was performed based onthe standard ASTM D5291 [24], using Flash EA 1112 Elemental analyzer, to evaluate the total carbon (C), hydrogen (H), nitrogen (N), sulphur (S), oxygen (O) percentages in the test samples after removal of volatile matters, the moisture and ash contents [25]. About 0.5 g of dried and milled sample, measured into a tin crucible with vanadium (v) oxide as catalyst, was dropped into the reactor in an oxygen environment to encourage an exothermic reaction. When temperature then rises to about 1800°C, the sample was combusted. The product of combustion was purified by a reactor packed with electrolytic copper and copper oxide, and then flowed into the chromatographic column, where separation occurred. The Nitrogen oxides and sulfur trioxide got reduced to elemental nitrogen and sulfur dioxide having excess oxygen retained. The gas blend containing $N_2$, $CO_2$, $H_2O$, and $SO_2$ gases were sent to the TCD where electrical signals were processed by 'Eager 300 software' to give percentages of nitrogen, carbon, hydrogen, and sulfur contained in the sample [18]. The samples were replicated three times in the experiment, and the average values of the results considered as the typical values.

The chemical elements that are present in minute quantity in the waste samples, called the trace – elements, were determined based on the standard ASTM C1111-10 [26] by using Inductively Coupled Plasma – Optical Emission Spectrometer (ICP – OES Perkin Elmer 8000).About 1 ml of each sample was measured into the digestion tubes to form a solution, and 1 ml of $HNO_3$was added to the solution and the tube inserted to Gerhardt – Kjeldatherm digestion machine, the temperature was maintained at about 180 o C, for 1hour.When the digests in the tubes became clear to light yellow in colour, the temperature was increased to 240 o C and further heated to dryness. The tubes were removed from the block and allow to cool. The ash was dissolved in 1 ml of concentrated HCL and add 10 ml of 5% $HNO_3$. After cooling, the aqueous solution of the sample was injected to ICP and was nebulized to a mist of finely divided droplet called aerosol. The ICP dissociated the waste sample into constituent atoms or ions by argon plasma and exciting them to a level where they emitted light of characteristic wavelength that was measured as a quantity. The light was resolved into its component radiation (by means of a diffracting grating) and intensity of the light was measured with a photomultiplier tube at specific wavelength for each element line. The intensity of the electron signal was compared to previous measured intensities of known concentration of the element and the concentration was computed in the data analyzer of the system. The mineral constituents in each sample was analyzed by ICP – Spec. using "WINLAB 32" software. The spectrometer data collection parameters was configured, viewed graphically and the results of the analysis was printed. The experiment was repeated three times on each sample of the waste components. The average values of the results were considered as the 'typical' values in parts per million (ppm).as presented in Table 6.

## 3.5. Thermal Characterization

The high heating value (HHV) measurement, was performed according to ASTM D5468-02 [27], using bomb calorimeter (*e 2k* combustion Calorimeter). About 0.5g of the component sample was measured into a crucible, placed in a high-pressure oxygen atmosphere metalliccylinder called a bomb. The mass of the test sample (0.5g) was inputted to the system through the computer input device connected to machine and the sample was fired to be completely consumed in the bomb. The result was later displayed on the screen after completion. The samples were replicated three times and the average values considered as the 'typical' heating values (MJ/kg). The high heating values of the combustible waste fractions is presented in Table 3. The low heating values was obtained by applying the mathematical model in Equation 5, adopted by [28][18].

$$LHV = \sum_{1}^{9} W_{\mathrm{j}} \times HV_{\mathrm{j}} \quad 5$$

Where typical heating values of MSW component- j and $W_{\mathrm{j}}$is the weight fraction (%) of component- j.

## 3.6. Multiple regression analysis

Multiple regression analysis was used to model the heating value of the municipal solid waste (MSW). The analysis was performed using GRETL statistical software adopting Ordinary lead square method (OLS) estimator and its diagnostic check [18]. Diagnostic check was performed by using Jarque-Bera test to determine the error distribution. The correlation of the regressors were examined by using variance inflation factor (VIF) for a diagnostic check of a problem of multicollinearity. Two models were developed, with the heating value (HV) as the dependent variable and fitted to independent variables derived from proximate and ultimate analyses. The equations of the models on proximate and ultimate analyses are presented in Equation 6 and 7 respectively.

The regression model for the proximate analysis is expressed in Equation 6:

$$H\hat{V} = -7.19477 + 0.116768 F\hat{C} - 0.34728\hat{M} + 0.151701 V\hat{M} \quad 6$$

where: HV is the heating value, FC is the fixed carbon percentage content of the municipal solid waste, MC is the moisture content percentage, and VM is the volatile matter percentage content.

The regression model for the ultimate analysis is expressed in Equation 7:

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

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

# 4. RESULTS AND DISCUSSION

## 4.1. Physical characterization

The MSW streams in Ilorin metropolis was characterized into nineteen fractionsnamely Grass/Trimmings, Food-residue, Nylon, Plastic-bottle, Packaging-box, Paper, Textile (rags), Leather, Bones, Cow-dung, Excrement, Polythene-sac, Toiletries (spent toilet tissue, pampers and sanitary pads), Tins/metals, Ceramics/glasses, Sands/ashes, Rubber, Wood and Others (unidentified crumped items with some organic matters)as shown in Table 1.During this study, the amount of waste predicted per day is 827000 tons with generating of 0.784 kg/capita/day. About 3,072 kg of MSW with volume of 15.4 $m^3$ was characterized. The waste analyzed for the period between May 2016 and August 2016 is 57.4 % of the entire characterization and the amount analyzed between November 2016 and February 2017 is 42.6% of the total characterization. During the wet season (May to August), Food waste has the highest proportion of 14.15% with generation rate of 0.081 kg/capita/person, followed by packaging-box of 12.31% with rate of 0.076 kg/capita/day and the least is Leather 0.079% with generating rate of 0.001 kg/capita/person. The analysis of November to February reveals that Nylon fraction has weight proportion of 19.42% with 0.1119 kg/capita/dayfollowed by Textile (rags) with 10.86% proportion at the rate of 0.07 kg/capita/day; and the least is Leather fraction of 0.06% proportion with 0.01 kg/capita/day. Food waste is much during rainy season because of new harvest which makes food items readily available and cheaper for many to afford. The high proportion of Nylon waste during dry season is because sachet water is available and affordable, and people take more water during the hot weather. Leather waste is the least in both seasons because, Leather is a very valuable material in Ilorin used for bags and shoes,and other ornaments.

**Table 1.** Physical characterization of MSW streams in Ilorin metropolis

| Waste Fractions | May-Aug Wt. (kg) | Nov-Feb Wt. (kg) | Total Wt. (kg) | Mean ± SD | Wt. % | Vol. $m^3$ | MSW/day (tons) | Kg/capita/ day |
|---|---|---|---|---|---|---|---|---|
| Food Waste | 249.60 | 68.90 | 318.50 | 39.8±35.3 | 10.4 | 1.43 | 85736.16 | 0.081 |
| Wood | 15.70 | 9.00 | 24.70 | 3.0±2.57 | 0.80 | 0.11 | 6648.93 | 0.006 |
| Paper | 96.30 | 89.40 | 185.70 | 23.2±8.17 | 6.04 | 0.93 | 49988.09 | 0.047 |
| Packaging-box | 217.30 | 80.30 | 297.60 | 37.2±22.8 | 9.69 | 1.38 | 80110.15 | 0.076 |
| Grass/Trimmings | 88.14 | 49.10 | 137.24 | 17.1±12.2 | 4.47 | 0.71 | 36943.27 | 0.035 |
| Textile (rags) | 130.90 | 142.90 | 273.80 | 34.2±13.9 | 8.91 | 1.42 | 73703.49 | 0.070 |
| Toiletries | 97.70 | 92.70 | 190.40 | 23.8±7.31 | 6.20 | 1.06 | 51253.27 | 0.049 |
| Feaces | 29.30 | 19.10 | 48.40 | 6.0±4.78 | 1.58 | 0.24 | 13028.67 | 0.012 |
| Cow-dung | 27.70 | 14.90 | 42.60 | 5.3±4.29 | 1.39 | 0.21 | 11467.38 | 0.011 |
| Nylon | 213.70 | 254.10 | 467.80 | 58.4±11.1 | 15.2 | 2.48 | 125925.83 | 0.119 |

| Waste Fractions | May-Aug Wt. (kg) | Nov-Feb Wt. (kg) | Total Wt. (kg) | Mean ± SD | Wt. % | Vol. $m^3$ | MSW/day (tons) | Kg/capita/ day |
|---|---|---|---|---|---|---|---|---|
| Polythene-sac | 96.62 | 66.90 | 163.52 | 20.4±8.13 | 5.32 | 0.84 | 44017.51 | 0.042 |
| Plastic-bottle | 192.80 | 107.90 | 300.70 | 37.5±25.3 | 9.79 | 1.42 | 80944.63 | 0.077 |
| Rubber | 3.60 | 1.70 | 5.30 | 0.6±0.44 | 0.17 | 0.01 | 1426.69 | 0.001 |
| Leather | 1.40 | 0.80 | 2.20 | 0.2±0.37 | 0.07 | 0.00 | 592.212 | 0.001 |
| Ceramics/Glasses | 35.70 | 46.60 | 82.30 | 10.28±4.3 | 2.68 | 0.44 | 22154.12 | 0.021 |
| Bones | 21.60 | 5.90 | 27.50 | 3.44±3.09 | 0.90 | 0.14 | 7402.652 | 0.007 |
| Tins/Metals | 89.30 | 55.20 | 144.50 | 18.1±14.9 | 4.70 | 0.67 | 38897.569 | 0.037 |
| Sand/Ash | 44.65 | 45.80 | 90.45 | 11.31±2.9 | 2.94 | 0.48 | 24347.994 | 0.023 |
| Others | 112.20 | 156.80 | 269.00 | 33.6±14.5 | 8.76 | 1.40 | 72411.391 | 0.069 |
| Grand Total | 1764.21 | 1308.00 | 3072.21 | | 100.0 | 15.4 | 827000 | 0.784 |

The components distribution of MSW in Ilorin is represented in Fig 2 which reveals that Nylon has the highest distribution with 15.23% and dispersion of 58.5± 11 followed by Food residue with 10.37% proportion and 39.8± 35.3 and the least is Leather 0.07% with dispersion of 0.2± 0.36.

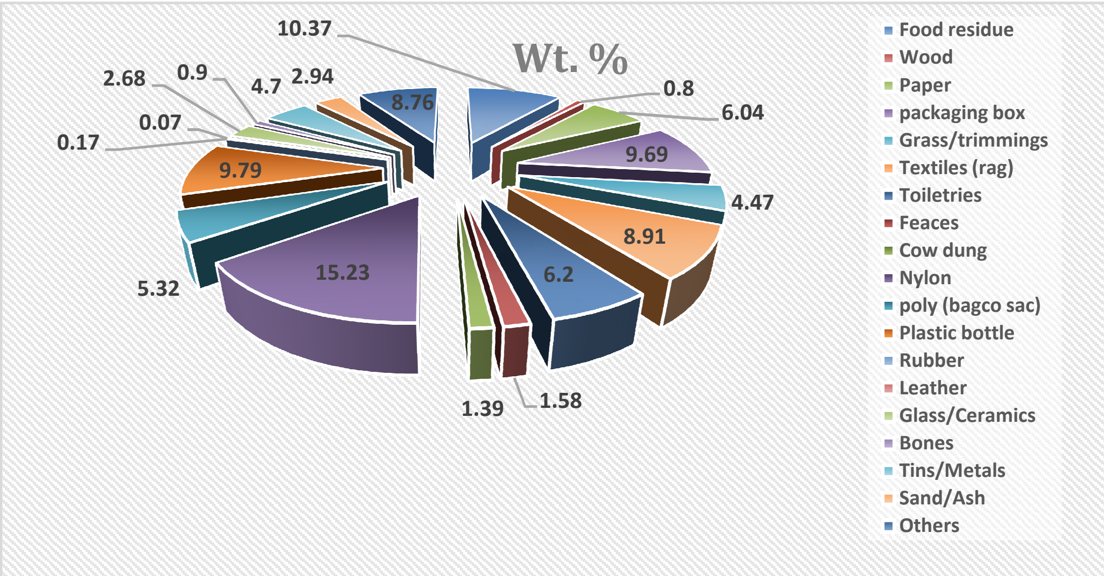


**Figure 2** Municipal Solid Waste Components Distribution

The combustible waste fractions in the entire wastes streams is presented in Table 2 and it is about 71% of the total waste characterized. This implies that Ilorin wastes streams have sufficient combustible fractions that can be utilized for energy recovery via combustion.

**Table 2.** The Combustible MSW fractions selected for Heating Value Analysis

| Waste Fractions | NOV-FEB | MAY-AUG | Total (Wt.kg) | Wt. % | Mean | Vol. $m^3$ |
|---|---|---|---|---|---|---|
| Food residue | 68.90 | 249.60 | 318.5 | 10.37 | 30±33.1 | 0.43 |
| Wood | 9.00 | 15.70 | 24.7 | 0.8 | 3.4±2.4 | 0.03 |
| Paper | 89.40 | 96.30 | 185.7 | 6.04 | 23±7.60 | 0.25 |
| packaging box | 80.30 | 217.30 | 297.6 | 9.69 | 34±21.4 | 0.40 |
| Grass/trimmings | 49.10 | 88.14 | 137.24 | 4.47 | 18±11.4 | 0.18 |
| Textiles (rag) | 142.90 | 130.90 | 273.8 | 8.91 | 31±13.0 | 0.37 |

| Waste Fractions | NOV-FEB | MAY-AUG | Total (Wt.kg) | Wt. % | Mean | Vol. $m^3$ |
|---|---|---|---|---|---|---|
| Nylon | 254.10 | 213.70 | 467.8 | 15.23 | 60±10.4 | 0.63 |
| polythene-sac | 66.90 | 96.62 | 163.52 | 5.32 | 19±7.60 | 0.22 |
| Plastic bottle | 107.90 | 192.80 | 300.7 | 9.79 | 38±23.6 | 0.41 |
| Grand Total | 868.50 | 1301.06 | 2169.6 | 70.62 | | 2.92 |

## 4.2. Thermal characterization

The high heating value (HHV)of the combustible waste fractions obtained from bomb calorimeter, is presented in Table 3. The result shows that the HHV is about 222 MJ/kg and the low heating value (LHV) about 20 MJ/kg. The heating value obtained is about 75 % equivalent of lignite, 59% of bituminous, 44% of crude oil, 40% of diesel and 42% of gasoline [29].

**Table 3.** Heating value characterization of combustible MSW fractions

| Waste Fractions | Food Residue | Wood | Paper | Carton | Grass | Textile | Nylon | Poly-sac | Plastic-bottle | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| HHV (MJ/kg) | 18.62 | 18.42 | 16.04 | 15.52 | 17.76 | 13.95 | 46.26 | 38.72 | 37.02 | 222.31 |
| Mean | 19±0.2 | 18±0.1 | 17±1.0 | 16±0.4 | 18±0.1 | 16±1.8 | 46±0.1 | 39±0.7 | 37±0.3 | |
| Wt. % | 10.44 | 0.84 | 6.16 | 9.74 | 4.63 | 8.92 | 15.24 | 5.33 | 9.98 | 71.28 |
| HV (MJ/kg) | 1.944 | 0.255 | 0.988 | 1.512 | 0.822 | 1.244 | 7.050 | 2.064 | 3.695 | 19.573 |

## 4.3. Physicochemical analysis

The proximate analysis in Table 4 shows that the average fixed carbon (FC) for the waste components is 57.7% that of volatile matter is (VM) is 29.1%, Ash is 8.1% and moisture content is 5%. Plastic bottle has the highest fixed carbon 98%, followed by Polythene 90%and the least is Grass/Trimmings 15%. Wood and Paper has the highest volatile matter of 59% followed by Grass/Trimmings with 52% and the least is Plastic-bottle with 1.3%. Grass/Trimmings has the highest Ash content of 23% followed by Textile with 20% and the least is Plastic-bottle with 1%. Wood has the highest moisture content of 12% followed by Grass with 10% and the least is Plastic-bottle with 0.0%. Plastic-bottle has the tendency of making more positive contribution to the net heating value because it has the highest fixed carbon content, the lowest ash and moisture content respectively. The polythene-sac is the waste fraction in the study with the highest heating value proportion of 39.35 MJ/kg, followed by Plastic-bottle 37.28 MJ/kg and the least is Textile (rags) 15.75 MJ/kg.

**Table 4.** Proximate Analysis of the Combustible Municipal Solid Waste Fractions

| Proximate Analysis | Packaging box | Nylon | Textile (rags) | Wood | Grass/ Trimming | Plastic bottle | Paper waste | Food residue | Polythene-sac |
|---|---|---|---|---|---|---|---|---|---|
| FC % | 65.3±2.2 | 80 ± 6.6 | 43± 9.3 | 27±9.5 | 15±0.9 | 98±0.4 | 24±4.8 | 89±3.1 | 90±2.6 |
| VM % | 16±2.71 | 18±7.10 | 31±10 | 59±10 | 52±8.4 | 1.3±0.4 | 59±5.6 | 3±2.2 | 6±3.1 |
| Ash % | 14±1.32 | 2±0.9 | 20±23 | 2±0.41 | 23±8.4 | 1±0.0 | 10±0.4 | 2±0.4 | 6±3.1 |
| MC % | 4.7±0.91 | 0.0±0.0 | 6.3±0.4 | 12±1.1 | 10±0.4 | 0.0±0.0 | 6±0.9 | 6±0.4 | 0.0±0 |
| HV ( $\bar{x}$) | 15.9±1.2 | 16±0.3 | 15±2.8 | 18±.03 | 18±0.2 | 37±0.7 | 17±0.9 | 18±0.5 | 39±0.6 |

In Table 5, the Ultimate characteristics reveal that the waste fractions have average elemental proportions of carbon (C) 29%, hydrogen (H) 0.11%, nitrogen (N)3.71% and sulphur (S) 0.4%. Food residue has the highest proportion of carbon content, 38% followed by wood 36% and the least is Polythene-sac 21%. Also Food residue has 0.16% as the highest proportion of hydrogen (H) content, followed by paper, packaging-box and plastic-bottle with 0.11% and the least is Grass/Trimmings with 0.01%. Paper and Food-residue has the highest nitrogen content (N) 5% followed by Textile (rags) 4.3% and the least is Polythene-sac with 2.7%. Sulphur (S) content is generally very low in all the waste fractions, the highest is 3.1% from Food-residue, followed by 0.1% from Nylon, Textile (rags), Wood and Plastic-bottle and the least is 0.05% from Polythene-sac. The carbon dominates the elemental content (28.9±0.68 Wt. %) and oxygen (0.74±0.00 Wt. %) of MSW. This shows that carbon be completely oxidized during combustion to form $CO_2$ and to release significant quantity of energy [30].

**Table 5.** The Ultimate Analysis of the Combustible Municipal Solid Waste Fractions

| Ultimate Analysis | MSW Fractions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Packaging Carton** | **Nylon** | **Textile (rags)** | **Wood** | **Grass/Trimmings** | **Plastic bottle** | **Paper waste** | **Food residue** | **Polythene-sac** |
| C % | 20.9±0.1 | 22±0.1 | 34±0.14 | 36±0.6 | 31±0.1 | 23.±0.03 | 35±0.1 | 38±0.4 | 21±0.11 |
| H % | 0.11±0.0 | 0.1±0.0 | 0.1±0.0 | 0.1 ± 0 | 0.01±0.0 | 0.11±0.0 | 0.11±0 | 0.16±0 | 0.1±0.0 |
| N % | 2.76±0.1 | 2.8±.02 | 4.3±0.0 | 4.5±0. | 3.86±0.1 | 2.93±0.0 | 5±0.24 | 5±0.10 | 2.7±0.01 |
| S % | 0.08±.03 | 0.1±0.0 | 0.1±0.0 | 0.1±0. | 0.07±0.0 | 0.1±0.02 | 0.08±0 | 3.1±0.0 | 0.05±0.0 |
| O % | 0.08±0.0 | 0.1±0.0 | 0.1±0.0 | 0.07±0 | 0.06±0.0 | 0.08±0.0 | 0.07±0 | 0.1±0.0 | 0.08±0.0 |
| HV ( $\bar{x}$) | 15.9±1.2 | 16±0.3 | 15±2.8 | 18±.03 | 18±0.2 | 37±0.7 | 17±0.9 | 18±0.5 | 39±0.60 |

The correlation analysis between the heating value (HV) and the proximate characteristics is presented in Fig. 3. The relationship shows that Nylon, Polythene-sac, Plastic-bottle component shave high heating values (HV) with corresponding high fixed carbon (FC), while waste fractions that include: Grass and Trimmings, Textile (rags), Paper and Wood have low HV and low proportion of FC. It implies that a percentage increase in FC content will invariably raise the net heating value. The waste components that have higher HV such as Polythene-sac, Plastic-bottle, and Food-residue have corresponding low volatile matter (VM). This is an indication that they have combustible volatile matter. Moisture contents in Nylon, Polythene, and Plastic components is at zero potential, while the moisture contents in other components are very low. This is an impression that their moisture contents would easily vapourize and dry off during combustion. Generally, the waste components have very low ash content, symbolizing that the ash generated during combustion will not impede the process of further combustion if the wastes are to be used for energy recovery via combustion.

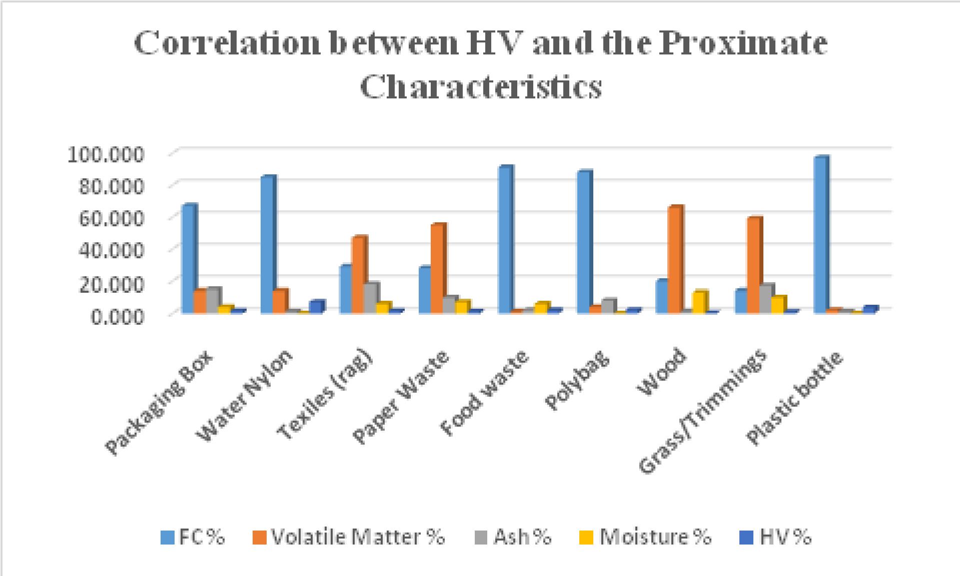


**Figure 3** The Correlation between Heating Value and Proximate Analysis of MSW

The relationship between HV and Ultimate analysis in Fig. 4, shows that carbon (C) contents of the waste fractions are much higher compared to other elemental constituents; this can contribute positively to the heating value potential. The average proportions of nitrogen (N) and sulphur (N) in the selected combustible waste fractions are 2.8 % and Sulphur about 0.2 % respectively; this indicates that the small average amount of Nitrogen and sulphur present will cause reduction of emissions during combustion.

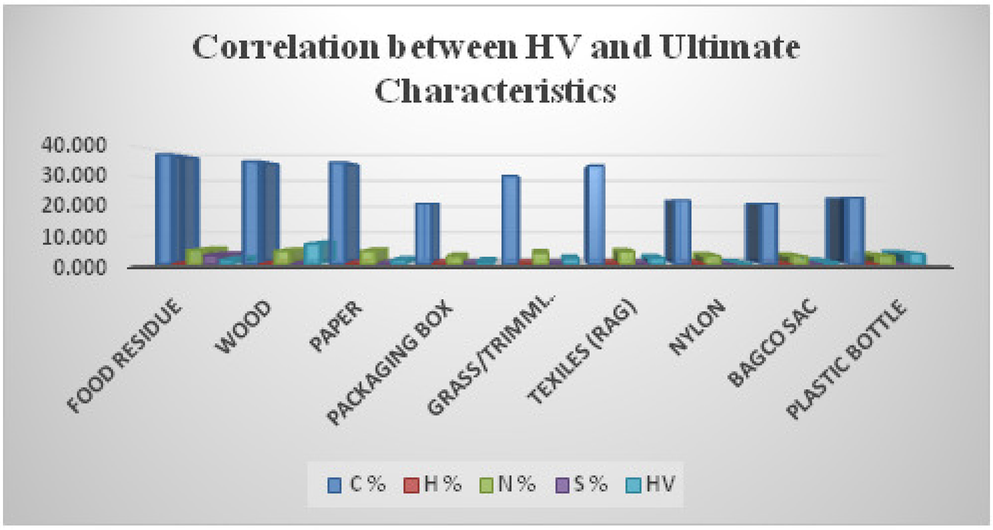


**Fig. 4:** Correlation between Heating Value and Proximate Analysis of MSW

## 4.4. Regression analyses

Modelling by regression analysis was performed to determine the effect of the physical and chemical characteristics of the combustible MSW fractions on the heating value. The analysis for proximate properties in Table 6 reveals that Fixed carbon and volatile matter have positive effect on heating value while moisture has a negative effect. About 1% increase in fixed carbon and volatile matter contents will increase heating value by 8 % and 37% respectively; while 1 % increase in moisture content will reduce heating value by 11%. The R-squared shows about 70 % of the variation in the response is explained by the regressors. The F test shows that the overall model fitted to the data is significant at 4 %.

**Table 6.** Regression model on Proximate analysis

| Estimation model 1 and its coefficient | | | | | |
|---|---|---|---|---|---|
| Model1: $HV = \gamma_0 + \gamma_1 FC + \gamma_2 M + \gamma_3 VM$ | | | | | |
| Independent Variables | $\gamma_i$ | Standard error | t-ratio | Pvalue | Regressors coefficient |
| FC__ | 0.117 | 0.077 | 0.077 | 0.19 | 0.078 |
| Moisture__ | -0.347 | 0.202 | 0.202 | 0.15 | -0.107 |
| Volatile_Matter | 0.152 | 0.096 | 0.096 | 0.18 | 0.368 |
| **constant** | -7.195 | 7.279 | 1.57 | 0.37 | -3.555 |
| Adjusted R-squared | 0.528 | Jarque-Bera test | 1.76 (0.42) | | |
| MAX(VIF) | 27.581 | | | | |
| | | | | | |

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

The result of regression analysis on ultimate properties in Table 7 shows that carbon and Sulphur have positive effect on heating value while hydrogen and nitrogen have a negative effect. About 1% increase in carbon and nitrogen will increase heating value by 79% and 11% respectively while a 1% increase in hydrogen and nitrogen decrease heating value by 30% and 619% respectively. The R-squared shows about 84% of the variation in the response is explained by the regressors. The F test shows that the overall model fitted to the data is significant at 5%.

**Table 7.** Regression model on Ultimate analysis

| Estimation model 2 and its coefficient | | | | | |
|---|---|---|---|---|---|
| Model 2: $HV = \lambda_0 + \lambda_1 C + \lambda_2 H + \lambda_3 N + \lambda_4 S$ | | | | | |
| Independent Variables | $\lambda_i$ | Standard error | t-ratio | P-value | Regressors coefficient |
| C__ | 85.08 | 23.25 | 3.659 | 0.02 | 79.08 |
| H__ | -28.97 | 71.95 | -0.403 | 0.71 | -30.16 |
| N_ | -666.13 | 182.26 | -3.655 | 0.02 | -619.09 |
| **S_** | 11.63 | 3.604 | 3.227 | 0.03 | 10.84 |
| **constant** | 1.381 | 9.46871 | 0.146 | 0.89 | 1.53 |
| R squared | 0.84 | Ftest | 5.144** | | |
| Adjusted R-squared | 0.671 | Jarque-Bera test | 0.4713 (0.7900) | | |
| MAX(VIF) | 161359.82 | | | | |

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

## 4.5. Trace Elements

These are chemical elements present in low concentration, measured in parts per million (ppm). Thirty of them were determined during the analysis of the combustible waste fractions, and are characterized in Table 8.These chemical elements include heavy metals like cadmium (Cd), mercury (Hg), and lead (Pb); major elements such as silicon (Si), aluminum (Al), potassium (K) and calcium (Ca) and minor elements like sodium (Na), magnesium (mg), iron (Fe) phosphorus (P). The major and minor elements have respective impact they make during formation of ash as the wastes combust. The ash melting point of the wastes fractions is raised by the impact of magnesium (Mg) and calcium (Ca.), while a decrease is caused by others. Al, K and Si may possibly form alum-silicates that could make the ash melting point to decrease thereby promoting the formation of slag. This must be put into consideration while making the choice of combustion technology. The low melting of the chlorides of the heavy metals thatmay have been formed can result to corrosion of mechanisms. The volatile compounds formed by elements which include Na, K, and the refractory elements such as Mg, Si and Ca. may remain in the char to form different shapes of ash particles.

**Table 8.** Characterization of the Available Trace-Elements in the Combustible Waste Fractions

| Trace Elements | Food Waste | Wood | Paper | Carton | Grass | Textile (Rags) | Nylon | Poly-sac | Plastic bottle | Wt. % | Avg. Wt. % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Na | 0.15 | 0.18 | 0.17 | 0.10 | 0.11 | 0.17 | 0.11 | 0.10 | 0.11 | 1.20 | 0.13 |
| K | 0.49 | 0.56 | 0.56 | 0.33 | 0.48 | 0.54 | 0.35 | 0.33 | 0.36 | 4.01 | 0.45 |
| Ca | 4.41 | 5.07 | 5.02 | 2.99 | 4.36 | 4.86 | 3.14 | 2.99 | 3.27 | 36.1 | 4.01 |
| Mg | 0.15 | 0.17 | 0.26 | 0.09 | 0.17 | 0.16 | 0.13 | 0.09 | 0.11 | 1.36 | 0.15 |
| Si | 2.06 | 1.73 | 2.35 | 1.30 | 2.50 | 2.83 | 1.33 | 1.36 | 1.59 | 17.04 | 1.89 |
| P | 0.15 | 0.18 | 0.07 | 0.06 | 0.25 | 0.25 | 0.13 | 0.14 | 0.14 | 1.39 | 0.15 |
| Mn | 0.44 | 0.16 | 0.16 | 0.98 | 1.80 | 1.86 | 1.21 | 0.99 | 1.58 | 8.42 | 0.94 |
| Fe | 1.26 | 1.45 | 1.43 | 0.88 | 1.28 | 1.39 | 0.89 | 0.85 | 0.94 | 9.44 | 1.05 |
| Zn | 1.53 | 0.60 | 0.59 | 0.35 | 0.52 | 0.57 | 0.37 | 0.36 | 0.39 | 5.31 | 0.59 |
| Cu | 0.84 | 0.16 | 0.10 | 0.15 | 0.14 | 0.16 | 0.02 | 0.09 | 0.20 | 1.30 | 0.14 |
| Pb | 0.34 | 0.05 | 0.05 | 0.03 | 0.04 | 0.05 | 0.03 | 0.03 | 0.03 | 0.63 | 0.07 |
| Ni | 0.83 | 0.49 | 0.49 | 0.29 | 0.42 | 0.47 | 0.31 | 0.29 | 0.32 | 3.90 | 0.43 |
| Mo | 5.91 | 4.50 | 4.46 | 2.65 | 3.87 | 4.31 | 2.79 | 2.65 | 2.91 | 34.1 | 3.78 |
| Se | 0.77 | 0.80 | 0.79 | 0.47 | 0.69 | 0.77 | 0.50 | 0.47 | 0.52 | 5.77 | 0.64 |
| Cd | 3.06 | 2.37 | 2.35 | 1.40 | 2.04 | 2.27 | 1.47 | 1.40 | 1.53 | 17.8 | 1.99 |
| Hg | 0.95 | 1.09 | 1.08 | 0.64 | 0.94 | 1.04 | 0.68 | 0.64 | 0.70 | 7.75 | 0.86 |
| Ag | 0.18 | 0.09 | 0.09 | 0.05 | 0.08 | 0.09 | 0.06 | 0.05 | 0.06 | 0.75 | 0.08 |
| Al | 0.13 | 0.15 | 0.15 | 0.09 | 0.13 | 0.15 | 0.10 | 0.09 | 0.10 | 1.09 | 0.12 |
| V | 1.34 | 1.54 | 1.52 | 0.91 | 1.32 | 1.47 | 0.95 | 0.91 | 0.99 | 10.9 | 1.22 |
| Au | 0.18 | 0.09 | 0.09 | 0.06 | 0.08 | 0.08 | 0.06 | 0.06 | 0.07 | 0.76 | 0.08 |
| Co | 0.72 | 0.22 | 0.22 | 0.13 | 0.19 | 0.21 | 0.14 | 0.13 | 0.14 | 2.09 | 0.23 |
| Cr | 0.23 | 0.04 | 0.04 | 0.02 | 0.03 | 0.04 | 0.02 | 0.02 | 0.02 | 0.46 | 0.05 |
| As | 0.16 | 0.07 | 0.07 | 0.04 | 0.06 | 0.07 | 0.04 | 0.04 | 0.05 | 0.60 | 0.07 |
| B | 0.36 | 0.42 | 0.41 | 0.25 | 0.36 | 0.40 | 0.26 | 0.25 | 0.27 | 2.96 | 0.33 |
| Ti | 0.66 | 0.76 | 0.75 | 0.45 | 0.66 | 0.73 | 0.47 | 0.45 | 0.49 | 5.43 | 0.60 |
| Sn | 0.59 | 0.68 | 0.67 | 0.60 | 0.58 | 0.65 | 0.42 | 0.40 | 0.44 | 5.02 | 0.56 |
| Sb | 0.89 | 1.02 | 1.01 | 0.60 | 0.88 | 0.98 | 0.63 | 0.60 | 0.66 | 7.26 | 0.81 |
| Cs | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.12 | 0.01 |
| Ba | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.07 | 0.01 |
| La | 0.08 | 0.07 | 0.07 | 0.04 | 0.06 | 0.07 | 0.05 | 0.04 | 0.05 | 0.53 | 0.06 |
| | | | | | | | | | | | |

The chart of the trace elements presented in Fig. 5,is the characteristic distribution of the nine combustible waste fractions investigated. The categories in the trace elements have different ranges in percentage by weight proportion. Heavy metals have a range of 0.07 ≥ 1.99, the major elements 0.12≥ 4.00 and the minor elements 0.13≥0.60.

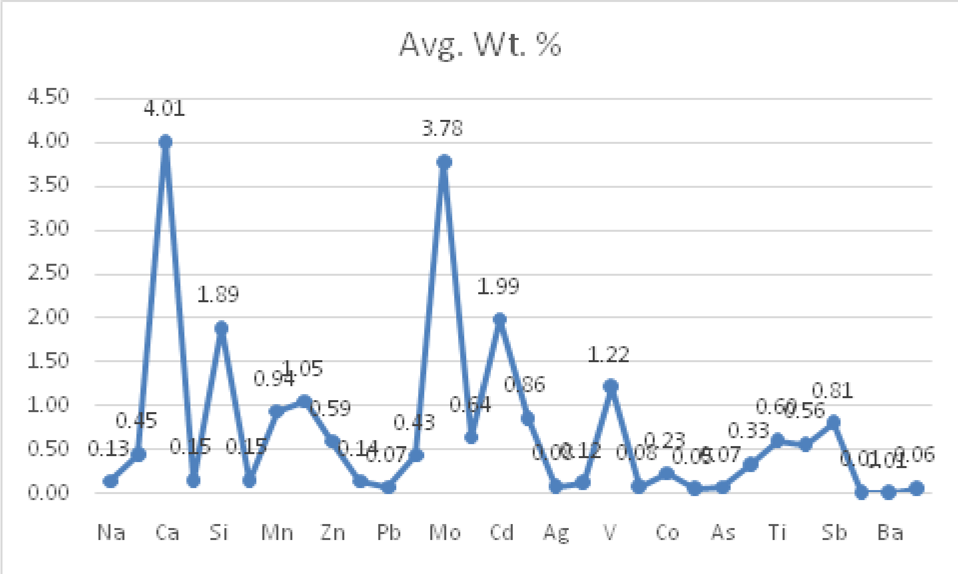


**Fig. 5.** Trace-Elements Distribution of the Combustible MSW Fractions.

## 5. CONCLUSION

The MSW generated in Ilorin metropolis is a huge one of about 827,000 tons per day, with 70% of it considered as combustible. The waste generated in Ilorin metropolis is sufficient of combustible fractions that can be used for energy recovery via incineration technology. The proximate analysis performed on the waste samples reveals that they contain more than 64% fixed carbon, 33 % volatile matter and 5 % of moisture content, while the ultimate analysis shows more than 29 % of carbon which can contribute to the calorific value of the MSW. The volatile matter content in the waste fractions is combustible and the available moisture content has tendency of drying off during combustion. The carbon content of the combustible waste fraction will completely react with the available oxygen content during combustion to form $CO_2$ and to release significant energy. Nitrogen is about 2.8 % and Sulphur about 0.2 %; the small average amount of Nitrogen and sulphur present will cause reduction of emissions during combustion. The high heating value of the MSW was determined using the bomb calorimeter to be about 20 MJ/kg, which is about 75 % equivalent of lignite, 59% of bituminous, 44% of energy in crude oil,50 % of energy contained in coal and about 100 % of the energy contained in biomass. It is concluded that the combustible MSW fractions in Ilorin MSW streams would serve as a reliable and sustainable renewable energy resource for heat or electrical energy production.

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## CONFLICT OF INTEREST

Authors declare no conflict of interest whatsoever

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