

Experimental Study of Abuja's Municipal Solid Waste for Energy Production Using Scanning Electron Microscopy Techniques

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ABSTRACT

In the face of the negative effects caused by the use of fossil fuels for energy production on the climate due to global warming, it becomes imperative to investigate the feasibility of using renewable energy sources such as municipal solid waste (MSW). This work investigates the potential of municipal solid waste (MSW) in Abuja, Nigeria, as a renewable energy source using scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analyses of selected samples for characterisation. The elemental constitution and potential combustion characteristics of Abuja's MSW were investigated in this work. The presence of key material elements in the study samples were used to predict incineration behavior and environmental implications. Also, grain size distributions and morphological characteristics that might affect combustion rates and incineration efficacy were determined in the study. Procedures followed in this work were according to ASTM E 1508 for the application of SEM for the identification of materials present in the bottom ash formed from the incineration of samples of Abuja's MSW. The plots generated indicate that silicon and iron were the major elements contained in the bottom ash formed with their values being highest at 49.5 and 19.55%, respectively. Also, the content of sulphur was shown to be very minimal in the study, being less than 3.5% for all samples tested. Abuja's MSW samples had grain size distribution in the range of 3.5 -16 mm, which would require shredding in order to have positive impact on combustion rate. This present work demonstrates sufficiently that Abuja's MSW will have a high level of environmental friendliness as a fuel due its low sulphur content, compared to fossil fuels.

KEYWORDS: Experimental Analysis, Scanning Electron Microscopy, Grain Size Distribution, Energy Dispersive X-Ray Analysis, Environmental Friendliness, Elemental Constitution

I. INTRODUCTION

Municipal solid waste has been proved as a veritable source of renewable energy for electric power generation (Ondachi et al., 2023; Malay et al., 2020). It is also known that this strategy of converting MSW to energy has potential to strongly reduce waste volume before transfer to landfills. It is also known that the challenge of greenhouse gas (GHG) emission linked to energy generation from fossil fuels may be ameliorated by using this strategy of converting MSW to energy (Traven, 2023; Wang & Azam, 2024). However, effective application of the waste-to-energy technologies requires that data on the MSW characterisation, especially with regards to its combustion performance be available. Scanning electron microscopy analysis is one of the important methods for MSW characterisation. The classification of municipal solid waste as a renewable energy source is a recognition of the fact that energy from MSW comes from organic material such as plants and animals. Plant and animal energy resources can be more quickly replenished than other energy sources such fossil fuels. It is known that fossil fuels take thousands

of years to form (Soeder, 2021). Photosynthesis helps plants to create biomass by using the carbon dioxide from the atmosphere which occurs within a time scale of a few years (Ondachi et al., 2024). At the end of the plants’ life, the carbon dioxide is returned into the air, hence, if organic waste is sent to final disposal without recovering energy from it, GHG will be added to the atmosphere during the decomposition of the waste. Application of the concept of waste-to-energy (WtE) will lead to provision of equivalent energy generation and thereby proportionally reduce energy generation using fossil fuels (Ondachi et al., 2024). Energy generation using from MSW therefore has potential to promote sustainable development.

Abuja’s built-up expansion rate has been on the increase, reaching about 30.93% by 2019 (Chukwurah et al., 2022). The city also is reported to have a population growth rate of about 5% as at 2020 (Bashir et al., 2021). This galloping rise in population hampers the provision of an MSW management system that is effective and efficient for the metropolis. Abuja’s urban population was estimated to be 1.69 million in 2020 (Bashir et al., 2021). with severe implications on waste generation and management. In most areas of Abuja, residents participate in a public-private partnership (PPP) program for the evacuation of MSW from their residences by placing collection bins at accessible points in their homes. The participating private entities collect and transport these wastes to landfills for final disposal, a process which is capital and labour intensive. Imam et al. (2008) reported that the aspects of collection and transportation makes up approximately 99% of the overall cost of managing MSW in Abuja even though the rate of waste collection is considered to be very at about 50% Imam et a. The remaining uncollected waste causes blocked drainages which leads to flooding and other negative impacts on public health. The Abuja Environmental Protection Board (AEPB) is the statutory organisation responsible for waste management activities in metropolis. Data for waste collection in Abuja for the period 2015 to 2019 is as presented in Table 1.

Table 1: AEPB annual MSW collection for Abuja (Tons) (Ondachi et al., 2023)

MONTH	2015	2016	2017	2018	2019
Jan	22229.06	21814.18	17966.754	20560.644	20615.868
Feb	22388.18	22539.58	17597.268	17310.852	17694.378
Mar	20354.06	23885.78	19286.28	20513.142	19974.942
Apr	23042.45	23342.90	18756.504	19995.3	21037.77
May	15306.5	22582.87	19975.176	21540.402	21046.194
June	21553.72	21682.91	19523.79	20218.068	19050.642
July	20998.22	21304.06	20676.24	21067.254	19895.85
Aug	23091.12	20951.66	20811.258	22201.218	21147.984
Sept	22674.6	21137.69	20316.582	20385.208	17216.55
Oct	24431.47	23867.06	20307.69	20645.352	24634.116
Nov	23811.84	22856.18	21255.156	20082.816	24955.164
Dec	23568.48	19308.74	20175.948	20223.684	24233.508
Total	263450	265274	236,649	244,744	251,503

Very little segregation of waste at source is presently practiced in Abuja (Ondachi et al., 2024). The minimally observed segregation of waste in the metropolis is being driven by scavengers for the purpose of recycling. Waste collection has become challenging in Abuja because of rising rates

of MSW generation, uncontrolled population growth, the city’s increasing rate of expansion, increasing effects of unapproved developments and slum settlements taken together with inadequate budgetary allocations [6]. Abuja’s MSW composition is as shown in Table 2.

Table 2: Abuja’s MSW composition

Waste constituent	Quantity (ton/yr.)	% wt.
Kitchen waste	161,207.7	33.87
Plastic waste	92,288.6	19.39
Paper waste	28,748.0	6.04
Metallic waste	60,589.7	12.73
Textile waste	21,465.8	4.51
Garden waste	64,302.2	13.51
Cardboards	20,371.1	4.28
Polythene	26,986.9	5.67
Total	475,960.0	100

This present work applying SEM experimental techniques to characterise Abuja’s MSW as an alternative energy source provides useful data that will assist in the creation of effective and economic strategies to solve the persistently rising challenge of MSW management in Abuja. The potential of Abuja’s MSW for electric energy development has not been adequately reported in literature. The scanning electron microscope (SEM) uses a focused beam of electrons to scan the surface of a material, thereby producing images that depict the material’s morphology. SEM provides high-resolution observations of microscopic and nanoscopic features, which makes the technology valuable in various science and engineering. The procedure provides useful data on parameters such as chemical composition, crystalline structure and morphology with the material’s electrical properties, hence providing footprints for the identification of the material. The SEM apparatus has comparatively greater magnification than most optical microscopes (not less than 200,000x). Also, the ultimate resolution is about 1.0 nanometre (Rullgård et al., 2011). The fundamental operating principle of the SEM is the application of kinetic energy to the electrons of a material’s sample. The energised electron beam interacts with the electrons of the test material to create appropriate signals that lead to the production of images with very spectacular clarity.

The study the feasibility of Abuja’s MSW as a source of renewable energy using the scanning electron microscopy analysis is the aim of this work. The study’s objectives were focused on determining the material composition of the MSW samples, incineration performance of the MSW and the determination of the composition of the ash formed by incineration of Abuja’s MSW for the purpose of characterization. The confirmation of the suitability of Abuja’s MSW as a renewable energy source for bulk electric power generation was also part of the study objectives. The set of data obtained from the study will help to determine Abuja’s MSW as a good fuel resource and also as a source for civil engineering construction materials after incineration for energy. The SEM analysis is a very useful tool in the characterisation of MSW especially as it provides data on the inert elements found in municipal solid waste samples which have significant influence on the energy yield of material and will determine the quantity and type of ash formed

after the incineration of the material. Formation of ash from the incineration of MSW depends greatly on the MSW's composition as indicated by its stream constituents, proximate analysis, grain size and the air-fuel ratio used.

II. LITERATURE REVIEW

Some research works have been carried out to study the challenges of waste management in Abuja metropolis. Aderoju et al. (2019) evaluated municipal solid waste generation in Abuja and observed that Abuja's MSW generation had an exponential growth rate due to the rapid urbanisation and high population growth taken together with the city's continually evolving economic and social status. In the study on Abuja's MSW Aderoju et al. (2019) applied incineration technology with energy recovery strategy as an effective solution reduce the volume of municipal solid waste MSW before final disposal, and as an additional solution to to the problem of inadequate supply of electric power to the city. Results from their work indicated that the higher heating value (HHV) for Abuja's MSW was evaluated as 38 MJ/kg. Ondachi et al., in their work on physicochemical characterisation of Abuja's MSW obtained the HHV of 22.4 MJ/kg, considering only organic fraction of the waste while volatile matter was found to be above 60% and an average fixed carbon content of about 26% for all samples tested (Ondachi et al., 2023b). Dickson et al. (2023) in another study on Abuja's MSW determined the HHV to be and the volatile matter to be 19 MJ/kg. Another study by Dodo & Ashigwuike (2023) shows that MSW generated in Abuja had energy potential 2,274.42 MWh/annum with a power potential of 28.43MW. Nwoke et al. (2020) in a study on MSW in Enugu, Nigeria, obtained an HHV of 15. 1 MJ/kg while the potential for electricity generation was estimated to be 573,439.090 MWh/annum.

Generation of energy from waste is the process of waste valorisation by using waste materials as fuel for producing heat and electrical energy. This may be achieved by converting the waste into a fuel source or by direct incineration of the waste with energy recovery (Themelis, 2023). Waste incineration for the purpose of energy recovery continues to be a very popularly applied waste-to-energy (WtE) technology in the world (Serrano et al., 2025). Renewable fuels obtainable from municipal solid waste conversion include gaseous fuel such as methane and liquid fuels such as ethanol and methanol. These derivatives may be used for energy generation applications or as feedstock for chemical production. Organic and textile streams of MSW which are known to have little recyclable value are ideal candidates to be converted to energy which makes WtE to be a veritable approach to sustainable management of MSW (Lawal et al., 2024). In addition, energy generation from MSW is globally taken to be a renewable and sustainable process (Lawal et al., 2024). Producing energy from waste will lead to a direct reduction in energy that would have been generated from fossil fuels which are known to be non-renewable and are the worst culprits of greenhouse gas emission to the atmospheric air (Freedman et al., 2024). Energy from MSW is principally obtained from the conversion of its organic fraction which is majorly biomass from plants and animal sources that can be regrown in a relatively short period of time.

Several studies have been undertaken on the techno-economic viability of converting waste to energy. Armoo et al., (2024) investigated the feasibility of producing electricity from a hybrid waste-to-energy pilot plant located in Ghana's Ashanti Region. Their study integrated three technologies: anaerobic digestion, pyrolysis and solar PV. The results obtained indicated that the investigated project had a high potential for investment attraction with a net present value (NPV) in excess of EUR 13 million and a payback period of 12 years with a levelized cost of energy (LCOE) determined as 0.3 EUR/kWh. Also, Shekarabi et al. (2025), in their work on the feasibility study of waste-to-energy conversion in a developing country's metropolitan areas determined that

MSW had potential to generate 466 kWh per day per ton. Chen & Wang, (2017), in their work on the potential contribution of municipal solid waste's incineration to electricity production and economic revenue in Taiwan determined that installation costs for WtE systems are much lower than other renewable energy systems. That study found that the engineering and procurement costs of a typical WtE plant is about 10% of the corresponding cost for the equivalent solar energy system and for wind energy plant, WtE is 34% cheaper (Chen & Wang, 2017). Due to improvements in technology, the average overall efficiencies of waste-to-energy plants have increased to about 22 – 30% for plants equipped to produce only electricity while for it is now about 30 – 60% for combined heat and power plant (CHP) (Carneiro & Gomes, 2019).

The scanning electron microscopy analysis is widely applied in the study of municipal solid waste for its conversion to energy. SEM may be used to characterize the MSW by determining the surface morphology and composition of materials, particularly on the feedstock before the energy conversion process and also on the bottom ash after the combustion process. SEM also helps in understanding how the various waste fractions behave during conversion process. This analysis has been found to be very essential for optimizing waste-to-energy technologies and ensuring efficient and environmentally friendly energy recovery. Ondachi et al., (2024) used SEM to characterise the bottom ash produced from the incineration of Abuja's MSW. The micrographs obtained show that silicon and iron are the more common elements found in the test samples. In their work, the maximum amount of silicon found present was 49.5% while iron was 19.5% for the Dutse-Alhaji sample. The test results from their work also determined negligible presence of silver and sulphur in the organic wastes generated in Abuja. The levels of silicon found in Abuja's MSW fall in the same range of values as for some Nigerian coals (Ondachi et al., 2024b). Since high level of presence of silicon inhibits slagging within furnace chambers, this is a good indication that Abuja's MSW will be good fuel for direct incineration for energy. A study by Wang et al applied SEM together with energy dispersive x -rays (EDX) to analyse and characterise deposits of ash from two WtE plants in Norway, focusing on elemental compositions and micro-structures of the MSW samples (Wang et al., 2017). The study provided data on concentrations of Ca, Si, K, Na, Cl and S in the ash formed from the conversion of the MSW. Also, Manohara & Belagali, (2017) characterised municipal solid waste using energy dispersive x-ray fluorescence (ED-XRF) together with SEM analysis. The XRF and SEM-EDS techniques have advantages of being non-destructive, time saving and economic tool with ability to estimate the percentage concentrations of several elements present in the samples.

III. METHODOLOGY

The methodology adopted in this study is discussed in this section:

A. Study Area

The Abuja Municipal Area Council (AMAC) is the study area for this work. AMAC is solely constituted by the Abuja metropolitan area and also serves as the capital city of Nigeria. Abuja is geographically situated in the central region of the country and located between latitudes 7° 49' and 8° 49' North. It is also between longitudes 7° 07' and 7° 33' East of the Greenwich Meridian within the Federal Capital Territory (FCT). Abuja's population is estimated to be 1.69 million people as at 2020 (Bashir et al., 2021). The FCT with a land area of 713 km² has six local governing areas, namely, Gwagwalada, AMAC, Abaji, Bwari, Kuje and Kwali. The Abuja Environmental Protection Board (AEPB) is central organisation in charge of managing solid waste in the metropolis. AMAC is shown in Figure 1.

Final disposal sites for MSW planned to serve AMAC include landfills located at Gosa, Ajata, Mpape, Kubwa and Karshi. The landfill at Gosa which was developed by AEPB and commissioned in 2005 is still operational. It is located close to the Idu industrial layout with a surface cover of about 90 hectares and is the largest and newest landfill in Abuja. It was originally planned to be fully developed as an engineered landfill with an expected capacity to handle all the MSW generated within the FCT.



Figure 1: The Study Area (Abuja Municipal Area Council) shown in a map of FCT

B. Experimental Procedures

MSW sampling

Samples of organic components of Abuja's MSW were taken from different locations in three (3) districts of other metropolis (Lugbe, Galadimawa and Dutse-Alhaji Modern Market). The sample locations are considered to adequately represent the entire study area for the goal of characterizing the waste. Samples from multiple locations were used for this work in order to study any inherent variations in MSW composition from various parts of the metropolis. Sampling techniques followed to ensure sampling consistency and scalability were according to the European Commission standards for municipal solid wastes sample preparation, SAM 002 (European Commission, 2021). In order to characterize and classify MSW samples from selected sites, the wastes were separated into homogeneous fractions from different components such as food wastes, garden wastes, wood, textiles, etc. by manual sorting. Only wastes that cannot be recycled were considered for laboratory tests. Hence only organic bio-degradable wastes were sampled. In general, 0.5 kg of sample was considered sufficient for laboratory analysis (European Commission, 2021).

Laboratory methods

Proximate analysis was conducted on the MSW samples following ASTM D3173 procedures and the results shown in Table 3. Laboratory procedure for proximate analysis [109, 110 & 111]

Determination of moisture content was done following ASTM-E871 standards as applied by Tursunov & Abduganiev, (202) in their work on MSW characterisation for renewable energy recovery from waste [110]. The sample's moisture content (M_w) on dry-basis was determined based on the mass loss of the sample before its oxidation. This was achieved by first letting the sample to dry in the sun for some days and then weighing about 500g out of it for laboratory use. At the start of the test about 5g is heated on a hot plate to remove any surface moisture. The initial mass, M_i , obtained is then recorded. This pre-dried sample is then put into a dish and dried in the hot air oven at a temperature of 105 °C for about 3 hours and then cooled in desiccators at normal room temperature. The sample is weighed again to obtain a final mass of dry sample, M_f . The moisture content is then calculated using Equation 1:

$$M_w = M_i - M_f \tag{1}$$

The amount of volatile matter present was determined by recording the loss in weight after heating the sample to 600 oC and is calculated using Equation 2 [109]:

$$\%VM \text{ at } 600^\circ C = \frac{M_i - M_b}{M_i} \times 100 \tag{2}$$

where

M_i = Initial mass of the sample,

M_f = mass of dry sample,

M_b = final constant mass of the sample before combustion.

The amount of ash formed is the residual matter and is determined by Equation 3.

$$\%A = \frac{M_a - M_o}{M_i} \times 100 \tag{3}$$

Where A = Ash content; M_a = Mass of Crucible with the ash, M_o = Mass of crucible without ash and M_i = Initial mass of the sample.

The amount of fixed carbon present in the MSW is calculated using Equation 4:

$$\% \text{ Carbon} = 100 - (\% \text{ Moisture content} + \% \text{ VM} + \% \text{ Ash content}) \tag{4}$$

Bomb calorimetry analysis was carried out on the samples using ASTM E711 with the results given in Table 4.

Also, the scanning electron microscope instrument was used to characterise the bottom ash formed in the incineration of Abuja's MSW samples according to ASTM F1372-93 (2020) procedures in this study as applied by Yaqoob et al in their work on pyrolysis oil (Yaqoob et al., (2021). The results of SEM analysis are as shown in Figures. 2 – 7 and in Tables 4 – 9.

IV. RESULTS AND DISCUSSIONS

A. Proximate Analysis

Results of the analysis for Abuja's MSW are as shown in Table 3 where values for all parameters fall in one range confirming minor differences in waste composition from the various district. Characteristic with MSW, the volatile matter is higher at above 60% for all samples.

Table 3: Abuja’s MSW Proximate Analysis

MSW Sample	% Moisture content	% Volatile matter	%Fixed carbon	% Ash content
Lugbe sample	7.7	63.0	25.4	3.9
Galadimawa	7.8	60.9	27.6	3.6
Dutse-Alhaji	7.9	62.8	25.6	3.7

B. Quantitative Energy Recovery Estimates

The potential for energy yield from the various MSW samples study as indicated by the higher calorific values is presented in Table 4 while summary of Abuja’s MSW generation parameters is presented in Table 5. The aggregate HHV of 22.4 MJ/kg shows that Abuja’s MSW will have energy yield that will compare well with coal (Garba et al., 2016). From Table 5, it is seen that Abuja has a daily MSW per capita waste generation rate of 0.77 kg/day/man and the combined stream of organic and textile waste with little recycling value constitutes 51.89% of total MSW generation for the city.

Table 4: Calorific Values of Abuja’s Organic Waste Samples

Sample ID	HHV (MJ/kg)	LHV (MJ/kg)
DUT	19.47	17.21
LUG	23.27	21.01
GAL	24.45	22.16
AGGREGATE	22.40	20.14

Table 5: Abuja’s MSW Generation Parameters

Parameter	Value
Per capita waste generation rate	0.77 kg/day/man
Estimated population (2022)	1,693,400
Daily waste generation	1,304 tons
Annual MSW generation	475,960 tons
Organic and textile fractions	51.89 %
Organic and textile fractions per annum	246,975.6 tons
Organic and textile fractions aggregate HHV	15.84 MJ/kg

Energy realizable from organic and textile fractions per annum	3.91×10^9 MJ/annum
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The total potential for energy generation from Abuja's MSW was determined to be 3.91×10^9 MJ/annum which can sustain a steam power plant of 54.58 MW capacity with positive economic indicators.

C. Abuja's MSW Bottom Ash Analysis

The percentage elemental composition of the bottom ash resulting from the combustion of Abuja's MSW was studied using a scanning electron microscope, applying the EDX analysis to the samples. Results of the tests are as shown in Figures 2 to 4. From the plotted micrographs, it can be noted that there high presence of silicon in the bottom ash of Abuja's MSW with Dutse-Alhaji samples having the highest value of 49.5 %. Galadimawa and the Lugbe samples show presence of silicon at 30.2 and 20.3%, respectively. The high silicon content is a good indication that Abuja's MSW will be friendly to equipment surfaces when used as a fuel. A high percentage presence of silicon in solid fuels indicates potential for effective fuel performance because it is known that high silicon content reduces tendency to cause slagging arising from ash deposition during incineration (Yang et al., 2022). This benefit comes from the silica (silicon dioxide) that is formed during the incineration process which increases the melting point of the ash produced, consequently leading to a reduction the slagging rate. Furnaces and boilers using solid fuels with low silicon levels therefore experience the problem of frequent fouling of their surfaces. The levels of silicon found in Abuja's MSW samples compare very well with values for some Nigerian coals where silicon contents range from 39.0% (Enugu), 44.8% (Okaba), to 49.4% (Maiganga) (Garba et al., 2016).

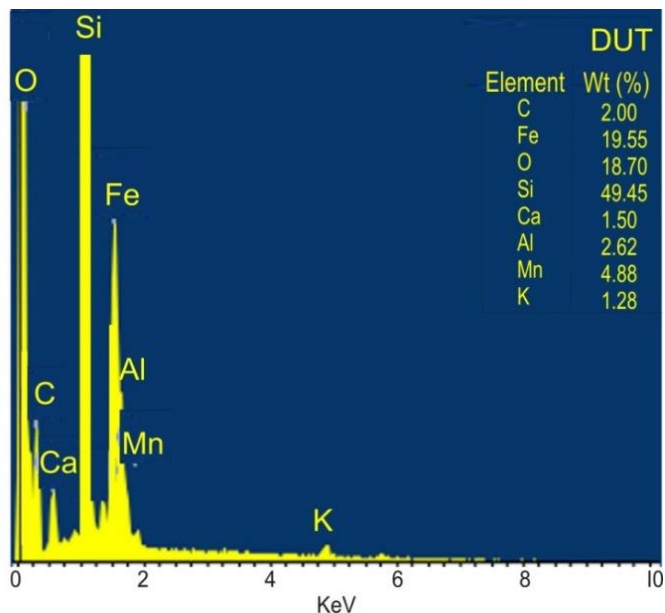


Figure 2: EDX Micrograph for Abuja’s MSW (Dutse-Alhaji sample)

There was no presence of unburnt carbon in the bottom ash formed from Galadimawa and Lugbe MSW samples while the Dutse-Alhaji sample had 2.0% (Figures 2 - 4). This excellent result regarding unburnt carbon in the bottom ash from Abuja’s MSW incineration indicates efficient and complete combustion of the samples. The result also suggests that the ash formed may easily be used together with Portland cement for civil construction without compromising structural strength since the compressive strength of such structures will compare well with that of structures erected with unmixed Portland cement (Suescum-Morales et al., 2022). Analysis of Abuja’s bottom ash also revealed very low presence of sulphur. There was no presence of unburnt sulphur in the ash of the Dutse-Alhaji sample while the ash of samples from Lugbe and Galadimawa contained 3.2 and 3.32%, respectively. The low content of sulphur in the bottom ash indicates that Abuja’s MSW will be environmentally friendly. This is because presence of sulphur in a fuel can lead to emission of hazardous oxides from furnaces and incinerators and even also at final disposal sites for the ashes. This study shows that Abuja’s MSW does not contain elements that may inhibit its application as a fuel. Also, it has been seen that Abuja’s MSW bottom ash will be a useful source of civil construction material Cho et al., 2020).

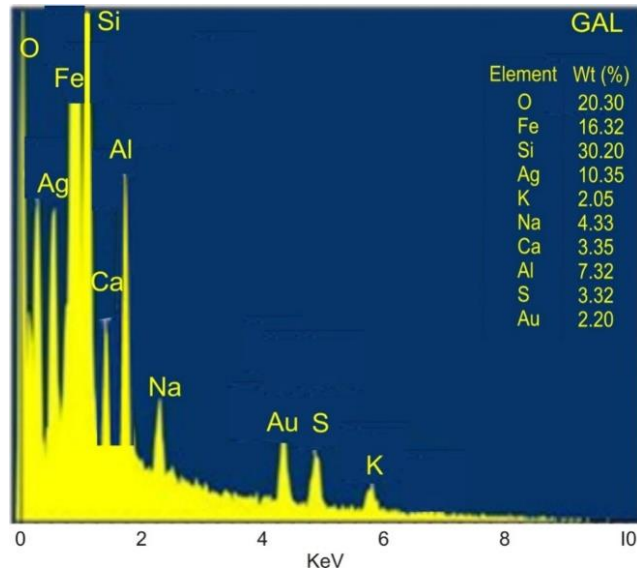


Figure 3: EDX micrograph for Abuja’s MSW (Galadimawa sample)

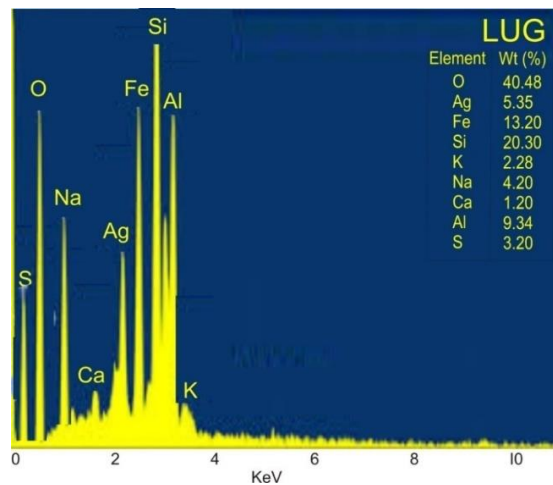


Figure. 4: EDX micrograph for Abuja’s MSW (Lugbe sample)

Results obtained in this present study for bottom ash characterisation are similar to results obtained by Loginova et al in their study of bottom ash composition from incineration of MSW in Netherlands (Loginova et al., 2018). Their study highlights the prevalence of silica in the bottom ash formed. Also, the results of this present study correlates well with similar study by Assi et al, (2020).

D. Abuja’s MSW Grain Size

Tables 6 – 8 present the ferret angles and grain sizes obtained for Abuja’s MSW in this study. Also, the SEM images for the same samples are as presented in Figures 5 - 7. The Dutse-Alhaji MSW sample presented the lowest average grain size of 3.5 mm while the Lugbe and Galadimawa samples have average grain sizes of 6.1 and 16 mm, respectively. These results compare well with

values of sizes (2 – 4 mm) obtained by (Loginova et al., 2018). Also, Mantovani et al., obtained 4mm grain size for MSW in Northern Italy, (Mantovani et al., 2023).

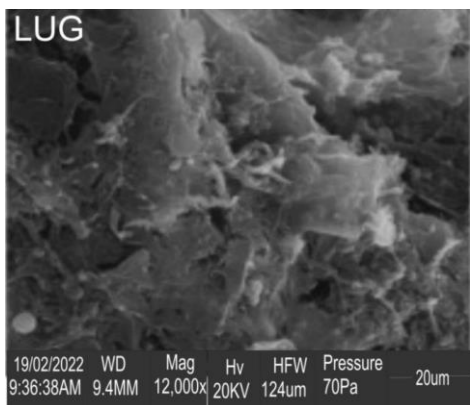


Figure 5: SEM Image for Lugbe MSW Sample

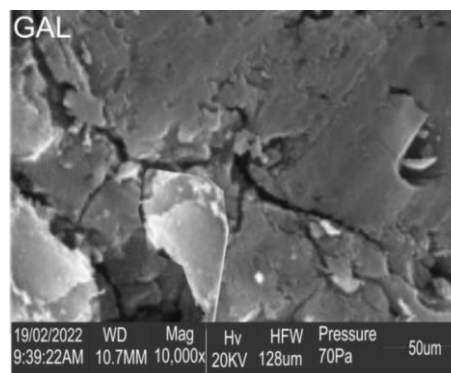


Figure 6: SEM image for Galadimawa MSW Sample

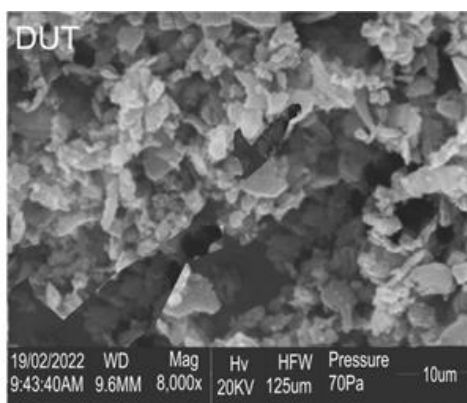


Figure 7: SEM Image for Dutse-Alhaji MSW Sample

From the results shown in Tables 6 –8, it may be observed that an aggregate of Abuja’s MSW will have an average grain size of the 8.5 mm. MSW as a solid fuel has much grain sizes than pulverised coal. It is reported that for most furnace applications, pulverized coal's average particle size ranges from 75 µm to 106 µm (Vishnoi & Mohapatra, 2018). Grain size is a crucial parameter in the combustion of solid fuels, since a smaller grain size results in a higher combustion rate leading to shorter burn-out periods (Ross & Blunck, 2022). The findings in this present study therefore suggest the need for Abuja's MSW to be shredded so as to improve the efficiency of combustion. Also, considering grain sizes pulverised coal will have higher combustion rate than Abuja's MSW. However, since it has been shown in this study that Abuja’s MSW has lower sulphur content, lower propensity for ash formation and lower greenhouse gas emission potential, it will be more friendly to the environment than coal. Additionally, it obtained at all most zero cost in addition to being renewable.

Table 6: MSW Image Analysis Parameters (Dutse-Alhaji sample)

Slice	Count	Total area (μm^2)	Average grain size (μm)	% Area	Perim.	Max. Feret	Feret X	Feret Y	Feret angle	Min. Feret
Black & white threshold	196	685227	3496.06	59.39	148.32	23.20	677.49	370.95	103.16	13.08

Table 7: MSW Image Analysis Parameters (Galadimawa sample)

Slice	Count	Total area (μm^2)	Average grain size (μm)	% Area	Perim.	Max. Feret	Feret X	Feret Y	Feret angle	Min. Feret
Black & white threshold	56	896077	16001.38	7.562	217.569	43.368	410.911	518.339	113.09	22.05

Table 8: MSW Image Analysis Parameters (Lugbe sample)

Slice	Count	Total area (μm^2)	Average grain size (μm)	% Area	Perim.	Max. Feret	Feret X	Feret Y	Feret angle	Min. Feret
Black & white threshold	140	856489	6117.78	71.58	118.237	24.787	524.629	626.379	117.241	12.833

It may also be observed from Tables 6 - 8 that Abuja’s MSW are relatively of low grain sizes with grain sizes ranging between 2 and 10 mm making up roughly 56.54% of the sample as a whole being obtained in this work. Caviglia et al. in their study using Turin's municipal solid waste concluded that about 10% of the MSW samples had grain sizes of over 20 mm (Caviglia et al., 2019).

E. Economic Analysis

MSW generation rate of 0.77 kg/man per day obtained in the study leads to the generation of 475,960 tons/annum. Organic and textile components of Abuja’s MSW which have little recyclable value were found to amount to 225,510 tons/annum (51.89% of total MSW generation in Abuja) and have a lower calorific value of 19.0 MJ/kg with annual energy potential estimated as $[3.91 \times 10^9]$ MJ/annum which can sustain a steam power plant of 54.58 MW. Cost analysis of energy generation by incineration technology gave a levelized cost of electricity (LCOE) of ₦29.025/kWh (US\$0.0387), net present value (NPV) of ₦200 million for a project life of 25 years with an undiscounted payback period of 10.83 years. The study showed that employing an incineration plant is an efficient method for the waste disposal while simultaneously generating

electric power. This makes MSW incineration a sustainable economic strategy for energy generation and MSW management for the future in Nigeria.

V. CONCLUSION

The characterisation study of Abuja's MSW by the application of SEM and EDX in order to determine how suitable it is as fuel for electric energy generation has been undertaken in this study. Abuja's MSW was incinerated in order to evaluate the elemental composition of its bottom ash in this study. Results obtained showed the value of volatile matter present to be higher than 60% for all samples while the potential for energy yield from the various MSW samples study as indicated by the higher calorific values is 22.4 MJ/kg. With the annual generation of organic waste determined for the city being 246,975.6 tons/annum Abuja's MSW has an energy generation potential of 3.91×10^9 MJ/annum which can sustain a steam power plant rated at 54.58 MW capacity with positive economic indicators. EDX analysis showed a high presence of silicon in the bottom ash of Abuja's MSW with Dutse-Alhaji samples having the highest value of 49.5 %.

From the values obtained for silicon content in the samples, Abuja's MSW will have efficient combustion performance as a fuel. The tendency for equipment surface fouling by slagging during incineration will be very low due to the high silicon presence. This is because silicon dioxide (silica) is formed during the incineration this silica increases the melting point of the ash formed from the combustion process hence only minimal slagging can occur. The study also showed that due to the low sulphur contents found in the same samples, the potential to emit toxic gases during combustion of Abuja's MSW will be low. The near-zero unburnt carbon content in the bottom ash from Abuja's MSW incineration indicates the relative ease with which efficient and complete combustion of the samples be achieved. Also, when the ash formed may easily be used together with Portland cement for civil construction without negative effects to structural strength. Also, it has been seen that the bottom ash from Abuja's MSW will be a useful source of civil construction material. With an average grain size of 8.5 mm, Abuja's MSW will require shredding if good combustion efficiency is to be achieved. Utilisation of Abuja's MSW will therefore lead to great economic benefits. Development of policy frameworks for the utilisation of MSW for electric power production and installation of a pilot plant for the testing of Abuja's MSW as a viable alternative fuel for emission control studies remain as future research directions for the continuation of this work.

VI. List of Abbreviations and Symbols

GHG	Greenhouse gases
MSW	Municipal solid waste
PPP	Public private partnership
AEPB	Abuja Environmental Protection Board
SEM	Scanning electron microscopy
HHV	Higher heating value
MJ	Megajoule
MWh	Megawatt hour
WtE	Waste-to-energy
Ca	Calcium
Si	Silicon

K	Potassium
Na	Sodium
Cl	Chlorine
S	Sulphur
EDX	Energy dispersive x-ray
XRF	X-ray fluorescence
FCT	Federal Capital Territory
AMAC	Abuja Municipal Area Council
ASTM	American Society for Testing and Materials
μm	Micrometer

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