Bioenergy: Physicochemical Properties and Energy Potential of Selected Wastes in Kumasi-Ghana

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***Abstract*—**Waste generation in Ghana is increasing exponentially due to high population growth, urbanization, and industrialization and waste management a problem. This study seeks to evaluate the energy generation potentials of the organic composition of the municipal waste in Ghana. This study evaluated physicochemical properties and energy potential of organic fraction of municipal solid waste (OFMSW), Abattoir solid waste (ASW), and restaurant solid waste (RSW) as a based to investigate the bioenergy potential of these wastes. The ultimate analysis of OFMSW, ASW, and RSW recorded % Carbon (45.20, 49.79, 55.55); % Hydrogen (5.53, 6.20 and 6.65); % Oxygen (47.02, 40.13, 33.58); % Nitrogen (1.70, 3.12, 3.42); and % Sulphur (0.55, 0.76 and 0.80) respectively. The higher heating values of OFMSW, ASW and RSW were evaluated based on the proximate analysis in MJ/kg (17.48, 16.74, and 17.53) and Ultimate analysis (14.79, 18.55, and 22.33) respectively. The BMP_{th} of OFMSW, ASW and RSW were evaluated based on the organic fraction composition (271.76, 201.36, and 379.59) and elemental composition (179.73, 243.44, and 326.73) respectively in mlCH4/gVS. Due to the higher moisture contents of these studied wastes, they might be unpreferable for thermochemical conversion processes but good feeds for biochemical conversion processes specifically, anaerobic digestio.

***Keywords*—** Anaerobic, Bioenergy. Energy Potential, Municipal solid Waste, Proximate Analysis.

I. Introduction

Ghana has its fair share of the municipal solid waste management menace. It is reported that Eleven (11) million MT/year of municipal solid waste is generated in Ghana [1, 2]. The majority of the municipal solid waste (MSW) from developing countries is generated from households (55% - 80%), market areas (10% - 30%), and institutions, among others [3]. Currently, apart from Kumasi, Tamale, and Takoradi, which have engineered landfill sites in place, the remaining towns, and cities, including the capital city Accra, do not have engineered landfills. As a result, only about 10 % of the waste generated is collected [2, 4], 11 % is burnt [5] and about 80% of the generated waste is either dumped in open fields or drains [6], which find their way to stormwater drains, rivers, streams, and eventually, the ocean.

It is emblematic in literature that substituting fossil fuel-based energy sources with renewable energy sources, which embraces bioenergy, direct solar energy, geothermal energy, hydropower, wind, and ocean energy (tide and wave), would gradually help the world obtain alternate sources of energy and even cleaner than the fossil fuels [7, 8, 9]. Domestic wastes and some industrial wastes could provide raw materials for several bioenergy conversion systems, all of which could recuperate beneficial energy while reducing landfill sites [10]. Bioenergy provides a wide range of applications and production of green fuel within the three states of matter (solid, liquid, and gas), and this explains constant acceptance of bioenergy [11]. Physical-chemical conversion processes, thermochemical conversion processes, and biochemical conversion processes are the main conversion routes in bioenergy [12]. This study seeks to evaluate the proximate analysis, ultimate analysis, higher heating value, theoretical biochemical methane potential of organic fraction of municipal solid waste, Abattoir solid waste, and restaurant solid waste as a based to investigate the bioenergy potential of these wastes.

II. RESOURCES AND METHODS USED

A. A. Sample Collection

The main waste samples considered in this study are organic fraction of municipal solid wastes (OFMSW), abattoir solid wastes (ASW), and restaurant solid wastes (RSW). OFMSW was collected from a prominent solid waste collection and recycling plant in Kumasi, Ghana. ASW was collected from Kumasi Abattoir. ROW was also obtained from composite samples made samples collected from some selected eateries in Greater Kumasi. All collection points are in Greater Kumasi, Ghana.

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B. Proximate Analysis

Proximate analysis was conducted on the waste samples to ascertain the moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC). These analyses were carried out at the Center for Energy and Energy Efficiency, Kumasi Technical University laboratory, Kumasi, Ghana. All samples' analyses were carried out in triplicates and the averages were reported.

C. Moisture Content (MC)

A 5 g quantity of waste sample was poured into a weighed crucible. The crucible and its content were weighed and placed in an oven at 105℃ for 2 hours. Then the crucible and its contents were cooled and weighed to obtain the difference after heating. After, the crucible and its content were placed in the oven again at 105℃ for 1hour, then it was removed from the oven cooled and weighed (This process was repeated till there is no change in mass of the crucible and its content after heating). MC was obtained using (1). This is the ASTM D14442 standard method. This was performed for all the studied waste samples.

$$MC\% = \left(\frac{M_2 - M_3}{M_2 - M_1}\right) * 100\% \quad (1)$$

Where,

M_1 = mass of empty crucible, g

M_2 = mass of crucible and its content before heating, g

M_3 = mass of crucible and its content after heating, g

Ash Content (AC)

The ASTM E1775-01 standard method was used to determine the AC of the studied wastes. A 5 g sample was poured into a weighed crucible and reweighed. The crucible and its content were placed in a muffle furnace at a 11℃ min^{-1} heating rate and held at 575℃ for 10 mins. The crucible and its content were allowed to cool in a desiccator and weighed. AC was calculated using (2). This was performed on all studied wastes samples.

$$AC = \frac{W_3 - W_2}{W_2 - W_1} * 100\% \quad (2)$$

Where, W_1 = mass of empty crucible, g

W_2 = mass of crucible and its content before heating, g

W_3 = mass of crucible and its content after heating, g

Volatile Matter (VM)

The ASTM E872-82 standard method was employed to ascertain the VM of the studied wastes. A 5 g of waste sample was poured into a weighed crucible and reweighed. The crucible and its content were covered and placed in a muffle furnace at 800℃ for 7 mins. The crucible and it content were cooled in desiccator and weighed after cooling. The VM of waste was calculated using (3). This was performed on all studied wastes samples.

$$VM = \frac{m_1 - m_2}{m_1} * 100\% \quad (3)$$

Where,

m_1 = mass of crucible and its content before heating, g

m_2 = mass of crucible and its content after heating, g

Fixed Carbon (FC)

Fixed carbon of the waste samples was calculated using (4)

$$FC = 100\% - (MC + AC + VM) \quad (4)$$

A. Ultimate Analysis, Heating Value and Biochemical Methane Potential

Ultimate Analysis

Ultimate analysis was conducted at the Agricultural Science laboratory, Kwame Nkrumah University Science and Technology, Kumasi, Ghana. The ASTM D3176 standard method was used to determine the hydrogen, carbon, nitrogen, and sulphur contents in the studied wastes samples. The oxygen content was estimated using (5).

$$\%O = 100 - (C + H + N + AC + S) \quad (5)$$

Atomic Ratios

C/N, H/C, and O/C ratios of the studied waste samples were estimated using (6), (7), and (8) respectively.

$$C/N = \frac{\%\ carbon\ content}{\%\ nitrogen\ content} \quad (6)$$

$$H/C = \frac{\%\ hydrogen\ content}{\%\ carbon\ content} \quad (7)$$

$$O/C = \frac{\%\ oxygen\ content}{\%\ carbon\ content} \quad (8)$$

Proximate and Ultimate Higher Heating Values

The proximate heating value of the studied wastes samples were estimated using Parikh et al. (2005) [13] equation and the ultimate heating value of the studied waste samples were estimated using Dulong's equation [14].

Theoretical Biochemical Methane Potential (BMP_{th}).

The modified Maynard methods of food analysis (Faithfull, 2002) was used to determine the organic fraction composition (OFC) of the studied wastes samples. BMP_{th} of the waste samples were estimated based on the OFC using an equation proposed by Lesteur et al. (2010) [15] and based on the elemental composition of the wastes using Buswell and Mueller equations [16].

III. RESULTS AND DISCUSSIONS

The Physicochemical properties and energy potential of OFMSW, ASW, and RSW were ascertained to help understand the use of these wastes in energy production and an expedient to maximize the beneficial merit of these wastes in energy generation. The data collected during this study are presented and discussed in this section.

A. Proximate Analysis

The proximate analysis of the studied waste samples are presented in Table I.

TABLE I
Proximate Analysis of Studied Wastes

Property	ASW	OFMSW	RSW
Proximate analysis, wt.%			
Moisture content	13.55	21.57	20.49
Ash content	1.31	3.69	1.69
Volatile matter	67.55	45.09	50.45
Fixed carbon*	17.59	29.65	27.37

Thermal decomposition, combustion, and anaerobic digestion are strongly influenced by volatile matter, that is, the higher the volatile content of the waste the more suitable the waste for bioenergy production via thermal decomposition and anaerobic processes [17, 18]. From table I, the volatile matter content of the studied wastes ranges from 45.09 to 67.55%, with ASW having the highest value while OFMSW has the lowest value. Also from table 1, ash content of the studied waste samples ranges from 1.31 to 3.69%, with OFMSW having the highest of 3.69%, while ASW has the least AC of 1.31%. These low AC recorded is a good factor for energy production, that is the low ACs implies higher heating values of the studied wastes as suggested by Mensah et al. (2022) [19]. RSW has the highest MC of 27.49%, followed by the OFMSW with MC of 20.57%, and ASW having the lowest MC of 13.55%. The vast MC difference between the studied wastes is due to the composition and the source of collection. Unlike thermochemical bioenergy processes, a relatively higher moisture content is preferred for biochemical bioenergy processes such as anaerobic digestion [20]. In contrast, these studied wastes are preferred feeds for anaerobic digestion based on the MC recorded. Table I reveals that the fixed carbon proportions, which ranges from 17.59% to 30.65, with OFMSW having the highest FC of 30.65%, with ASW has the lowest FC of 17.59%. And it could be deduced from table 1 that there exists a directly proportional relationship between AC and FC across the studied wastes samples.

B. Ultimate Analysis

TABLE II
Ultimate Analysis of Studied Wastes Samples

Ultimate analysis, wt.%	ASW	OFMSW	RSW
Carbon, C	49.79	45.20	55.55
Hydrogen, H	6.20	5.53	6.65
Nitrogen, N	3.12	1.70	3.42
Sulphur, S	0.76	0.55	0.80
Oxygen, O*	40.13	47.02	33.58
Higher heating values, MJ/kg			
Based on proximate data	16.74	17.48	17.53
Based on ultimate data	18.55	14.79	22.33

The suitability of a biomass or solid waste for thermochemical bioenergy processes and anaerobic digestion could be ascertain by data obtained from ultimate analysis [21, 20]. Table II reveals that the studied wastes have low carbon except RSW which a relatively higher carbon content hence its relatively higher heating value based on ultimate analysis. Also, it could be deduced from table II that hydrogen content and oxygen content have directly proportional and indirectly proportional relationship respectively with the heating value, that is a higher hydrogen content, and a lower oxygen content causes an increase in heating value of the waste. This trend was also achieved in the work done by Kumar and Patel (2008) [22]. Furthermore, from table II, all studied wastes recorded lower amount of nitrogen (1.70-3.14%) and sulphur (0.55-0.80%). This shows that these wastes will generate very low amounts of NO_X and SO_X when used to generate energy or other fuels through bioenergy processes [23].

C. Atomic Ratios

TABLE III
Atomic Ratios of the studied wastes

Atomic ratios	ASW	OFMSW	RSW
H/C	0.12	0.12	0.12
O/C	0.81	1.04	0.60
C/N	15.96	26.59	16.24

The optimum C/N ratio of biomass for anaerobic digestion ranges between 20 and 35 [24]. Per the results obtained in this study, only OFMSW waste (26.59) falls within this range. It has also been found that a mixture of high and low C/N ratios of biomass is recommended for anaerobic digestion and therefore the mean average of the three studied wastes (19.6) is good to be utilized for biogas production [20]. H/C and O/C ratios have an inversely proportional relationship with energy density [25]. That is, higher H/C and O/C ratios causes a decrease in energy density with calorific value of a biomass or this study waste, from table 3, a similar trend is shown and confirmed as RSW which recorded O/C has the highest calorific value while OFMSW which has the smallest calorific value due to its higher O/C ratio

D. Biochemical Methane Potential

TABLE IV
Theoretical Biochemical Methane Potential of Studied Wastes

Waste Sample	%Carbohydrate	%Protein	%Lipids	BMP_{thOFC} (mlCH4/gVS)	BMP_{thAtc} (mlCH4/gVS)
ASW	22.32	19.53	1.17	201.36	243.44
OFMSW	50.41	10.65	0.96	271.76	179.73
RSW	54.85	21.37	4.53	379.56	326.73

Theoretical methane estimation is apt as it helps the researcher to evaluate the methane potential of the samples before performing the actual experiments [17]. The theoretical

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BMPs of ASW, OFMSW, and RSW waste samples estimated using their organic fractions (BMP_{thOFC}) and ultimate compositions (BMP_{thAtc}) are presented in Table 1V. Ali *et al.* (2018) [26] found that BMP_{thOFC} and BMP_{thAtc} methodologies give more accurate theoretical methane results as compared to the chemical oxygen demand (BMP_{COD}) methodology. The results obtained in this study were compared with other studies in literature [27, 17]. For instance, the BMP_{thOFC} of OFMSW (271.76 mlCH_4/gVS) and RSW (379.56 mlCH_4/gVS) were higher than BMP_{thOFC} of waste mixture (244.36 mlCH_4/gVS) recorded by Mbugua et al. (2020) [17]. It can therefore be deduced that this study results showing higher composition of theoretical methane fractions and could yield more biogas from the substrates studied. Apart from the huge margin observed for OFMSW, the results of the remaining two samples, specifically ASW and RSW, do not differ much for the two methodologies employed.

IV. CONCLUSION

The bioenergy potential of organic fraction of municipal solid waste (OFMSW), Abattoir solid waste (ASW), and Restaurant solid waste (RSW) were ascertained and their suitability for energy generation has been established. This was done through the data obtained from various characterizations, such as, proximate analysis, ultimate analysis, proximate and ultimate higher heating values, organic composition fractions, theoretical biochemical methane potential and atomic ratios. The ultimate analysis of OFMSW, ASW, and RSW recorded % carbon (45.20, 49.79, 55.55); % hydrogen (5.53, 6.20 and 6.65); % oxygen (47.02, 40.13, 33.58); % nitrogen (1.70, 3.12, 3.42); and % sulfur (0.55, 0.76 and 0.80) respectively. The higher heating values of OFMSW, ASW and RSW were evaluated based on the proximate analysis in MJ/kg (17.48, 16.74, and 17.53) and Ultimate analysis (14.79, 18.55, and 22.33) respectively. The result obtained from this study shows that these studied wastes have favorable fixed carbon, above 13% and ash content less than 2% for thermochemical conversion processes. Theoretical biochemical methane potential values obtained for OFMSW, ASW, and RSW, also suggest that these wastes are favorable for anaerobic digestion for production of biogas with low NO_X and SOx generation when combusted. Although, the studied wastes are favorable all bioenergy processes, the higher moisture contents of these wastes them unpreferable for thermochemical conversion processes but good feeds for biochemical conversion processes specifically, anaerobic digestion.

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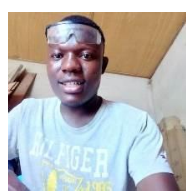

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