

Comparative study of calorific value of municipal solid waste of Suleja, Niger State, Nigeria using different mathematical model

¹Ahmad, U. M., ¹Usman, A. M., ¹Abdulhamid, S. and ¹Dodo, M. S.

¹Department of Mechanical Engineering, Modibbo Adama University Yola, Adamawa State Nigeria

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Abstract:

The calorific value of Municipal Solid Waste (MSW) is essential in the design of waste to energy facility. The calorific value of a solid fuel is obtained using the bomb calorimeter. However, the calorific values can also be obtained from mathematical models using the elemental composition of the biodegradable component of MSW. However, models are specific and can give divergent results. The study intends to compare the calorific values obtained from Dulong, Dulong-Berthlot, Bento mathematical models. Six Samples of MSW were collected from the dumpsite from Suleja, Niger State Nigeria, the calorific values of the samples were determined using the bomb calorimeter, the proximate and ultimate analysis were determined. The calorific values of all the samples were calculated based on Dulong, Dulong-Berthlot and Bento's models. The calorific values obtained from the bomb calorimeter experiment for the samples S1, S2, SS3, S4, S5 and S6 were 16.10 MJ/kg, 18.70 MJ/kg, 20.76 MJ/kg, 21.64 MJ/kg, 24.65 MJ/kg and 22.81 MJ/kg respectively. The result shows that Bento's underestimate the calorific values in all samples, whereas Dulong's model predicts three of the values within $\pm 4\%$. Dulong's model was found to be predicting the calorific values of Suleja MSW better.

Corresponding author

Ahmad, U. M.

umarbabayolaj@gmail.com

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1. Introduction

Municipal solid wastes (MSW) are defined as unwanted materials or wastes generally produced from households and other municipal related activities [1]. The rapid explosion in population, and other factors can lead to the increase in MSW generation [2]. These waste generated poses health and environmental challenges for Municipalities [3]. One of the waste management technologies which is commonly employed is waste-to-energy conversion processes which includes incineration, gasification, and pyrolysis [4]. Calorific value is a crucial factor in determining whether the waste generated is suitable for energy recovery as well as in analyzing the effectiveness and viability of the waste to energy systems [5, 6].

Understanding the amount of heat energy contained in municipal solid waste and its potential for energy recovery requires knowledge of its calorific value, which is a measurement of the heat energy released per unit mass of a substance upon full combustion [7]. This is to make it easier to choose the right technology and to maximize energy recovery from trash [3].

Calorific value is defined as "the heat energy released per unit mass of a substance during complete combustion (8). It is typically expressed in units of energy per unit mass, such as Megajoules per kilogram (MJ/kg)

Due to variations in waste composition, climatic conditions, trash generation patterns, and waste treatment techniques, the calorific values of MSW might fluctuate

regionally and over time [4, 9]. A thorough investigation was carried out in China by [10] highlighted regional variations in waste composition and, consequently, calorific values.

The Experimental determination of calorific value by using bomb calorimeter is the most reported in literature [6], however, empirical models may be used to estimate the calorific values of MSW, such models may be based on the proximate and ultimate analysis of the waste [10]. These methods are often simpler, quicker and provide accurate results [11]. The most used are Bento, Dulong and Dulong-Berthlot models. Bento's model is based on proximate analysis whereas Dulong and Dulong Berthlot are based on ultimate analysis.

This paper compares the calorific values obtained from the bomb calorimeter experiment to the calorific values obtained using Bento, Dulong and Dulong-Berthlot empirical models.

2. Methodology

2.1 Study area

Suleja L.G.A is located between Latitude 9°12'1.17" N and Longitude 7°10'20.25" E. It shares boundary with Gurara to the North-West, Tafa to the East in Niger State and Gwagwalada, Zuba to the south, in Federal Capital Territory. Suleja is about 20km North of Abuja the Federal Capital of Nigeria and about 100km North East of Minna the State Capital of Niger State. Suleja has tropical climate and summers are much rainier than the winters in Suleja. The average annual temperature is 26.3 °C and the average

rainfall is 1328 mm. The driest month is December. The highest precipitation occurs in September; with an average of 272 mm. March is the warmest month of the year with average temperature of 29.0 °C. The lowest average temperature is in August and is about 24.5 °C. The MSW management practiced is open landfilling [6].

2.2 Materials and equipment

P6310 Bomb calorimeter Setup, weighing scale, RHF 1500 Oven, CNHS analyser and Experimental determination of calorific value using bomb calorimeter. Waste sample from dumpsite in Suleja, the sample collected were collected and sorted manually to remove the inorganic materials (e.g. Glass, metals etc.) according to ASTM D5231. Each constituent was cut into small pieces or grinded. The samples were then weighed and placed into the bomb calorimeter. The bomb calorimeter was assembled, and the cap was securely tightened. Oxygen pressure was then injected into the bomb calorimeter until the pressure reached 25 atm. The bomb calorimeter was placed into an adiabatic calorimeter bucket containing water with a fuse (ignition) wire of about 7cm long passing through the sample with both ends of the wire attached to two electrodes of the bomb calorimeter. A thermometer was placed inside the water jacket after bomb calorimeter as connected to a power source. The stirrer was then started and allowed to run five minutes before the temperature reading was taken. The fire button was then pressed at the fifth minutes of the experiment. At the end of the fifth minutes, a stop watch was started and the temperature was recorded at one minute interval. Subsequent temperature readings were recorded continuously until the difference between successive readings became constant for at least three minutes. After the last temperature reading was taken, the calorimeter was stopped, the cover was lifted and components were removed and wiped with a clean cloth.

2.3 Models and analyses

The results obtained from the experiment were used to calculate the calorific value of the municipal solid waste as described in the manual (Parr 6310 Bomb calorimeter manual). The gross calorific value was calculated using equation 1 [12].

$$CV = \frac{\Delta t \times w}{m} \quad (1)$$

Where; CV is the calorific value, Δt is the corrected temperature rise, w is the water value of the bomb calorimeter and m is the mass of the fuel. The experiment was repeated for six (6) samples S1, S2, S3, S4, S5 and S6.

2.3.1 Proximate analysis

1kg each of the MSW sample was sealed and taken to the National Geographic Survey Agency, Kaduna for proximate and ultimate analysis. Proximate analysis was done according to ASTM 3173-3175 to determine the gross component of moisture, volatile matter, fixed carbon, and Ash content.

2.3.1.1 Determination of moisture content

Organic waste sample of 5g was placed in an oven at 105°C for two hours. The sample was then cooled in a desiccator and reweighed. The moisture content was calculated using equation 2 [13].

$$M = \frac{S-B}{S} \times 100 \quad (2)$$

Where; M is the moisture content, S is the mass of sample before heating and B is the mass of sample after heating.

2.3.1.2 Determination of volatile matter

The remaining organic sample used for moisture determination was covered in a crucible and heated in a furnace for 2 hours. The crucible was later taken out of the furnace and cooled in a desiccator and reweighed. The volatile matter was determined using equation 3 [13].

$$V = \frac{A-B}{A} \times 100 \quad (3)$$

Where; V is the volatile matter, A is the mass of sample after moisture content analysis, B is the mass after heating.

2.3.1.3 Determination of ash content

Ash content was determined by placing the remaining organic sample from volatile matter into a furnace at 575°C for an hour for combustion. All carbon was burnt, and the sample was cooled in a desiccator and then reweighed. The ash content was obtained using equation 4 [13].

$$\text{Percentage Ash} = \frac{A-B}{C} \times 100 \quad (4)$$

A is the mass of the container with residue in g, B is the mass of the empty container and C is the initial mass of sample with moisture.

2.3.1.4 Fixed carbon content

Fixed carbon in fuel was determine by the subtraction 100 from the moisture, volatile matter, and ash contents it was determined using equation 5 [14].

$$FC = 100 - M - V - ASH \quad (5)$$

Where; FC is the fixed carbon content, M is the moisture content, V is the volatile matter and ASH is the ash content.

2.3.2 Ultimate analysis

Ultimate analysis was done on a using the CHNS analyser which employs classic oxidation, decomposition, and reduction technique. Organic sample of 0.5 g was dried at 105°C for 3 hours, cooled in the desiccators, and then grounded to powder form by using pestle and mortal and letter formed into pellets. The pellets were then put in the CHNS analyser to determine the percentage composition of C, H, N and S. oxygen content was determined using equation 6 [14].

$$O = 100 - (C + H + N + S + ASH) \quad (6)$$

Where; O, C, H, N and S are the percentage of Oxygen, Hydrogen, Nitrogen and Sulphur respectively, ASH is the ash content.

2.4 Models

2.4.1 Bento's model:

This is based on proximate analysis, the calorific value is given by the equation 7 [15].

$$CV = 44.75V - 5.85W + 21.2 \quad (7)$$

Where V is the Volatile matter and W is the moisture content.

2.4.2 Dulong's model

This is based on the ultimate analysis. The calorific value can be obtained using equation 8 [16]

$$CV = 81C + 342.5(H - \frac{O}{8}) + 22.5S \quad (8)$$

2.4.3 Dulong-Berthlot's model

This is also based on ultimate analysis. The calorific value is given by equation 9 [17].

$$CV = 81.37C + 345[H - \frac{(O+N-1)}{8}] + 22.2S \quad (9)$$

Where CV = Calorific value (CV_{gross}), C, H, N, O and S are Carbon, Hydrogen, Nitrogen, Oxygen and Sulphur. The variation of CV_{model} from CV_{bomb} was calculated as a percentage using equation 10 [18].

$$\frac{CV_{model} - CV_{bomb}}{CV_{bomb}} \times 100 \quad (10)$$

3. Results and discussion

The proximate analysis and ultimate analysis are presented in Table 1 and 2 respectively. Proximate analysis of the samples shows that S1 is having the highest moisture content of 36.8% and the lowest is S3 with 25.9%. the lower the moisture content the higher the calorific value of the waste. The moisture content is in the range of 26.7%, 29.6% and 32.5% obtained for Katsina, Dutse and Kano respectively [17]. However, the values are lower than the 55.8% and 38.37% obtained for INEX and GOSEPA in Gombe respectively [15]. This shows that the moisture content of the MSW is dependent on the location and the habits of the residents.

It has been found that when the moisture content of MSW is less than 45%, its volatile matter content is around 40% and the fixed carbon content is less than 15%, it is suitable for energy recovery via incineration [19]

The ash content for S2 was the lowest with 8.78% and highest for S3 at 14.63%, lower ash content means lesser inert materials in the waste. The ash content was found to be between 5-15% recommended for incineration [14].

The higher the amount of hydrogen in a waste sample, the higher the quantity of energy it will generate, and the higher the quantity of oxygen in a waste sample, the lower its energy potentials [15].

Table 1: Proximate analysis of the dumpsite

Component	S1	S2	S3	S4	S5	S6
%M	36.8	30.25	25.9	34.2	32.77	28.5
%V	39.45	43.45	44.4	36.78	46.12	41.81
%ASH	12.63	8.78	14.63	13.51	9.1	13.15
%FC	11.12	17.53	15.07	15.51	12.01	16.54

Table 2: Ultimate analysis of waste samples

Component	S1	S2	S3	S4	S5	S6
%N	1.0242	1.1523	1.2004	1.1523	1.2004	1.058
%C	35.72	33.64	40.78	33.64	40.78	38.82
%H	6.5341	7.41	7.8892	7.41	7.8892	9.2154
%S	1.25	1.19	1.13	1.19	1.13	1.08
%O	6.0417	8.8977	7.1304	8.8977	7.1304	8.1766

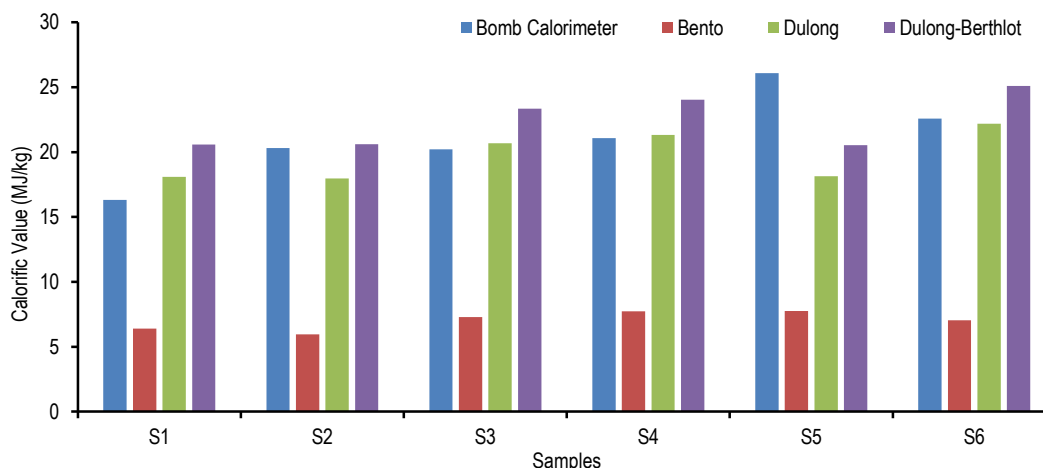


Figure 1: Comparison of Experimental calorific value with predicted calorific value

The calorific values from the bomb calorimeter experiment were found be 16.10 MJ/kg, 18.70 MJ/kg, 20.76 MJ/kg, 21.64 MJ/kg, 24.65 MJ/kg and 22.81 MJ/kg for S1, S2, SS3, S4, S5 and S6 respectively. From Figure 1 above, Bento's model was seen to highly under predict the actual calorific value in all cases. Dulong's model was found to predict three of the values within $\pm 2.4\%$ accuracy and five of the values within $\pm 12\%$ accuracy as in Table 3. Dulong Berthlot does on the other hand predict only one value within $\pm 2.4\%$ accuracy and four values within $\pm 16\%$ accuracy. These are in contrast with Daura [20] which shows that Bento model give higher calorific values compared to Dulong's and (21) which shows that Bento's model gives a better prediction of the heating values for Tanjung city in china. The result is also in line with Kumar and Samaddar [22] and Abd Kader et al., [23] that Ultimate analysis-based model showed maximum prediction accuracy, while proximate analysis-based model showed minimum.

Table 3: Percentage error from measured calorific value

S/No	Bento	Dulong	Dulong – Berthlot
1	-60.83	+10.85	+26.22
2	-70.86	-11.45	+1.43
3	-63.88	+2.38	+15.56
4	-63.30	+1.16	+13.97
5	-70.24	-30.44	-21.22
6	-68.84	-1.77	+11.19

4. Conclusion and recommendation

Accurate knowledge of heating value is necessary for the design and successful operation of thermal conversion systems. According to Mboowa et al., [14], municipal solid wastes having calorific values of 11-17 MJ/kg or even higher are recommended for use as refuse-derived fuel (RDF). Various models were used in determining the calorific value of Suleja MSW, however Dulong's model provide the closest values when compared with the calorific values obtained from bomb calorimeter experiment. A better model can be obtained using linear regression or artificial neural network.

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