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DETERMINATION OF ENERGY CONTENT OF PLANT BIOMASS FOR DOMESTIC AND SMALL-SCALE INDUSTRIAL HEATING APPLICATIONS

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ABSTRACT

Determination of the calorific values and elemental contents of plant biomass are important in considering their heat energy potential and environmental friendliness. It is also important in performance modelling calculations on thermal systems. This study measures the calorific values of twenty (20) biomass comprising herbaceous plants and agricultural waste with the aim of understanding their energy potential to be used as alternative fuels for small-scale industrial and domestic heating activities. The direct measurements of the calorific values were made using Bomb calorimeter (model 6100 series) and estimated from the ultimate analysis data of the samples. The relationships between the calorific value and the total carbon and hydrogen contents of samples were also investigated. The analysis results indicate that palm kernel shell and locust bean pod have the highest energy values of 41.1165 MJ/kg and 36.2230 MJ/kg respectively. Camel foot and soybean stalks give the lowest energy values of 6.0484 MJ/kg and 5.3353 MJ/kg respectively. The energy values of about 60% of biomass samples are in the range of 15-21 MJ/kg in agreement with the widely reported values in the literature. Further analysis indicates that the experimental measurements do not excellently agree with the values estimated using correlation equations and, in most cases, the experimental data is higher than that estimated using correlation equations. However, about 60% of the data points computed using the two equations agree closely. The study shows that the calorific values of all samples are strong function of their total carbon contents and have no direct relationship to their total hydrogen in agreement with some theoretical formulations. This work is important in biomass energy development.

Keywords: Plant biomass, Calorific value, Heating applications, Bomb calorimeter

INTRODUCTION

Energy is a vital ingredient for development and a powerful engine of social and economic change in any country or region. It is the power derived from the utilization of physical or chemical resources, especially to provide heat and light or to work machines. To address the various energy challenges associated with non-renewable fuel, many countries have indicated a commitment to renewable energy development particularly solid biofuels that are sustainable, cheap, efficient, safe and geographically diversified. The advantage of solid biofuels is their domestic origin, and potential for reducing total dependence on oil and gas economy. It also offers benefits of regional development, and social structure, especially to developing countries like Nigeria (Hudgson 1997). Despite the international commitment to sustainable energy development, the Nigerian government and the local communities have only indicated a partial concern to renewable energy development derived from biomass. Plant biomass is derived from natural processes that are constantly replenished. It has a unique characteristic of natural abundance and is geographically diversified. This influenced its higher demands and utilisation than any other fuel, particularly in developing countries like Nigeria. Globally about 9% of the total energy used in 2012 is from traditional biomass like fuelwood (IEA, 2013). In Nigeria, about 57% of the total energy used is from biomass with the remaining percent from other sources. The major energy-consuming activities in Nigerian households and small-scale businesses are cooking, lighting and the use of electrical appliances. Cooking accounts for about 91% of household energy consumption, lighting uses up to 6% and the remaining 3% goes to the use of basic electrical appliances (Sambo, 2009). To date, the national energy supply in Nigeria is entirely dominated by fossil fuels. Renewable energy resources are grossly underutilised despite their huge potential.

Domestic heating represents the largest area of energy consumption in many developing countries around the world. For example, most communities in Nigeria are predominantly rural and the economic strength of people is quite low so many people lack the energy for their bare necessities of life as the population cannot afford to buy natural fuels (oil and gas). They often rely on wood, herbaceous plants/grasses, agricultural waste and animal dung as their main fuels for domestic cooking and heating. Fuel wood and charcoal are extensively used in cities. Many of these biomasses are thrown away or burnt in the air during bush clearing without utilising it as a source of heat energy. Their abundance resources can be utilised effectively to do many useful works and derive economy. Plant biomass is a versatile energy source that can improve energy supply by diversification and has the potential to mitigate greenhouse gas (GHG) emissions that was identified as the major contributor to the current global warming problem. Direct research on the heat energy content or calorific value of various plant biomass resources will give additional insight on the effective utilisation of the plant resources.

The calorific value (CV) of a fuel is an expression of the energy content, or heat value, released when a unit value of it is burnt in air (McKendry, 2002; Jones 2009). It is the amount of heat in, or work obtainable from, a unit amount of the energy resource. It is another important parameter, which determines the quality of an energy source. The calorific value is also called the heating value. It will be used interchangeably in this article. The energy resources being analysed in the present study are low moisture content fuels which contain carbon, hydrogen and oxygen in major concentrations, while

sulphur nitrogen and a number of other elements are in minor concentrations. Determination of the heating values and the elemental composition of biomass are important in determining their heat energy potential and environmental impact. It is also important in performance modelling calculations on thermal systems (Kumar and Pratt, 1996). Compared to coal, plant biomass, in general, has high moisture, higher oxygen content, lower sulphur and nitrogen contents, lower energy content and ash. Currently, biomass fuel remains the only reliable energy source for heating activities in Nigeria. This is due to its domestic origin, availability and low cost. The continued use of biomass for heating instead of other fuels like cooking gas, kerosene and electricity may be connected to the unavailability of other sources due to corruption and poor energy management, higher demands due to a steady increase in population without a corresponding increase in energy production. There is also poverty which made it difficult for many citizens to switch to other alternatives. Despite an attempt by the Nigerian government through an energy masterplan in 2005 (ECN, 2005) to exploit some of the available energy sources and add to the energy mix, the available review shows that no significant progress is achieved in reducing the projected energy use by 20% by 2020 and equally meet 20% of the country's electricity needs with renewable energy. This study is an attempt to measure the energy content of twenty plant biomass that are available in Nigeria to understand their potential to be used as alternative fuels for domestic and small-scale industrial heating applications. The biomass fuels considered in the present study are those that are grossly underutilised or misused/abandoned in Nigeria despite their reasonable quantities. This study is a rider to the earlier article by the authors (Ismaila *et al*, 2013) and is geared to boost the interest of the Nigerian government and local communities toward developing alternative sources of energy in the form of biomass that could be grown for energy production or processed from waste for heating applications to our households and small-scale industrial applications.

MATERIALS AND METHODS

The Raw Materials

The raw materials used in the present study are twenty different plants biomass made up of herbaceous plants and agricultural residues obtained from farmlands within Phase II of Ahmadu Bello University, Zaria and Samaru, Zaria local community. The collected samples are mosquito repellent plant/lemon balm, Camel foot, orange peel, Tamarind bark, Bamboo, Locust bean pod, Deleb palm nut husk, Palm kernel shell, Senegal tea plant/wild coffee, Bambara groundnut shells, African mahogany, Gmelina bark, Soybean stalks, Wheat Husks, Corn cobs, Groundnut shells, Rice Husks, sawdust, maize husks, and Guinea Corn Husks. They were kept at room temperature and used in experiments without undergoing any pretreatment to represent the actual condition of the biomass by which they are used as fuel for heating activities.

Sample preparation

The samples were cut into small pieces of approximately 1 cm using stainless steel scissors and sun-dried separately for about one week to remove moisture from the samples. The moisture or water content can reduce the combustion efficiency of solid biomass and it is therefore important to remove it before the experiment. The dried samples were carefully pounded in a wooden mortar and pestle and then sieved into 1 mm mesh-size powdered samples in accordance with the procedure of Zakari *et al.* (2013). The powdered samples of about 2 g of each sample are kept in a clean polyethene bag to prevent moisture absorption before Bomb calorimeter measurements at the Chemical Engineering Department of Ahmadu Bello University, Zaria.

Analytical procedure for Bomb measurements

The calorific value of the twenty biomass samples were determined using Bomb calorimeter (model 6100 series manufactured by Parr Instrument Company) and estimated using the correlation equations developed by Boie (1953) and Tillman (1978. The bomb method is a direct measurement of energy content of samples. The machine gives the energy value which includes the latent heat of vapor emitted from the specimen. The calorimeter measurement is based on the oxygen depletion calorimetry which relies on the precisely known air flow through the system. In the process, the fuel mass loss rate is converted to heat energy and the heating value of the fuel is readily computed and appears on the display screen of the machine. A full system of Bomb calorimeter consists of a cup sample container, high precision thermometer, a screen display for data entry and operation control, a 1108 oxygen tank, a built-in semi-automatic system for charging the bomb with oxygen, the Dewar which prevents heat flow from the calorimeter to the surroundings, communication ports for printer, a fuse wire ignition circuit connected to the bomb and a stirrer. All steps in the test are managed by a dedicated microprocessor control system programmed to operate the machine in either faster dynamic mode or equilibrium mode.

The bomb calorimeter is calibrated by combusting 1g mass (99.5% purity) of benzoic acid. About 2000 ml of distilled water at room temperature is placed in the calorimeter sample holder and placed within the adiabatic jacket. The bomb is immersed in the water and a Nickel fuse wire (~10 cm) of known heat of combustion per unit length (0.9813 kcal/g) caused the ignition of the benzoic acid. The experiment was run and the measured heat of combustion ((H_c) of benzoic acid was found to be 6318 cal/g. This is actually within the range specified in the instrument's manual for standardization of the machine. As the calorific value of this acid is determined, the bomb is standardized and ready for use to calculate the heat of combustion of any compounds.

About 0.025 g of each sample is burned in the machine. As the fuel burns, heat the surrounding air which expands and escapes from the calorimeter through the copper tube. When the air is escaping, through the tube, it also heats up the water outside the tube. The temperature change in water along with the bomb factor are used to calculate the calorific value of the sample burned.

Measurement of total Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen

The calorific value of the biomass sample can also be determined from the ultimate analysis data of the sample. This is the indirect method of determining the energy content of the sample by substituting its elemental composition from the empirical correlations which relate the heating value and total elemental contents. The major elements of interest are carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulphur (S). These elements were determined from analytical experiments at the Soil Science Department, Institute of Agricultural Research, Samaru, Zaria. The total carbon of each sample was determined in the combustion analysis apparatus and the total nitrogen content for all samples was determined by Kjeldahl's method. The total sulphur was determined by a slight modification of the Carius method. The total hydrogen contents of all the samples were determined using the neutron

reflection technique. In the technique, a 1Ci ^{241}Am-Be neutron reflection facility at the Centre for Energy Research and Training (CERT), Zaria is employed in estimating the total hydrogen content of each sample. The total oxygen content of each sample was obtained by subtraction from Equation 1.

$$\%Oxygen = 100 - (\%C + \%H + \%N + \%S_{organic}) \quad (1)$$

Detailed analytical procedures for estimating the five listed elements from the agricultural biomass samples are described elsewhere (Ismaila, 2012).

The indirect measurement of calorific values of all samples were made using the empirical correlations developed by Boie (1953) and Tillman (1978) given by Equations 2 and 3 respectively.

$$CV\ (MJ/kg) = 0.3517C + 1.1626H + 0.1047S + 0.0628N - 0.111O\ MJ/kg \quad (2)$$

$$CV\ (MJ/kg) = 0.4373C\text{-}1.6701\ MJ/kg \quad (3)$$

where C, H, O, N, and S in the above equations represent carbon, hydrogen, oxygen, nitrogen and sulphur contents of biomass expressed in mass percentage on a dry basis.

RESULTS AND DISCUSSION

Calorific value and ultimate analysis results of biomass samples

The results of elementary and calorific values of all samples measured with the bomb calorimeter are listed in Table 1. The table indicates that palm kernel shell and locust bean pod have the highest energy values of 41.1165 MJ/kg and 36.2230 MJ/kg followed by Gmelina bark and Tamarind bark with energy values of 25.9424 MJ/kg and 21.3035 MJ/kg respectively. The biomass with the lowest energy values are camel foot and soya bean stalks which show 6.0484 MJ/kg and 5.3353 MJ/kg respectively. The higher energy values recorded for palm kernel shells, Gmelina and Tamarind bark which are tree barks may not be unconnected to their densities as compared to camel foot and soya bean stalks which show small energy values. The density of a fuel greatly determines its calorific value. The densities of most hydrocarbon fuels are quite high when compared to those of agricultural biomass. It is for this reason that the energy densities of petrol, diesel and cooking gas are higher than those of wood and plant biomass. Their energy densities are in the range of 41 -44 MJ/kg. The calorific value of coal is 30 MJ/kg. The table indicates that other biomass such as corn cobs, groundnut shells, saw dust and African mahogany have an appreciable energy value in the range of 18-19 MJ/kg. These biomasses are in most cases thrown out as waste and have not been used to generate heat for domestic and small-scale industrial heating applications. The data presented in Table 1 shows that the energy values of about 60% of biomass samples are in the range of 15-21 MJ/kg in agreement with the widely reported values (Ismaila *et al.*, 2013; Zakari *et al*, 2013; Annamalai, *et al.*, 1987; Kumar and Benjamin, 1996; Chaniwala and Parikh, 2002 and in line with the standard measurements by the American Standard of Testing Materials (ASTM). It is only 15% and 25% of the samples are above and below the widely reported range of 15-21 MJ/kg. The higher energy values of 41.1165 MJ/kg and 36.2230 MJ/kg observed in palm kernel shells and locust bean pods may be connected to their density and chemical contents. It may also be connected to their experimental conditions as the reported values go beyond the widely known values for most biomass. The calorific value of 30-32 MJ/kg is for coal/coke compounds. Previous studies by Zakri *et al*. (2013) report a heating value of 26 MJ/kg for cocoanut shells which is quite similar to palm kernel shells.

The ultimate analysis data for the 20 biomass samples is presented in Table 1. From the table, it can be seen that C, H and O constitute the major elemental composition of plant biomass while S and N formed the least. The carbon and oxygen content are important in biomass combustion. Higher carbon content indicates good grade biomass fuel while higher oxygen contents tend to lower the calorific value in most cases. This has been discussed in Section 3.3. The table shows that the total carbon and oxygen contents of the samples vary from 75.982- 16.152 (wt%) and 74.1921-19.4272 (wt%) respectively. Maize husks give the highest carbon content and least oxygen value while soybean stalk has the highest oxygen value and least carbon content.

The total hydrogen varies from 6.0182-2.1089 (wt%) with locust bean pods showing the maximum value and soya bean stalks gives the minimum value. Higher hydrogen content in the biomass may not be a problem unless it comes as moisture. Since hydrogen is an energy carrier and its complete combustion gives water, it should therefore increase the calorific value. The theoretical formulations by Boie (1953), Channiwala and Parikh (2001), and Yin (2011) indicate a positive relationship between the sample's hydrogen and the calorific value. Table 1 shows that the total nitrogen varies from 0.140-2.014 (wt %) with the rice husk having the highest and bamboo giving the least value. Soya beans indicate higher sulphur contents of 6.0847 (wt%) and groundnut shells give the smallest value of 0.014 (wt%), rice husks following with the 0.015 (wt%). Higher sulphur and nitrogen content has no advantage in biomass combustion as they tend to increase the release of toxic gases such as HCN, NO_x, SO_2, aldehydes and acrolein which may have adverse effects to living organisms and the environment. The ultimate analysis results for the range of biomass tested are in good comparison with the ones obtained by the Authors (Ismaila *et al.*, 2013; Peter, 2002; Kumar and Benjamin, 1996; Chaniwala and Parikh, 2002) for different biomass samples.

Table 1: Ultimate analysis and calorific value of the biomass samples

S/N	Sample Name	C%	H%	S%	N%	O%	Calorific Value (MJ/kg)
1	Mosquito repellent plant/ Lemon balm	36.001	5.4973	1.969	1.400	55.1327	12.4266
2	Camel foot	33.082	4.4728	5.025	0.742	56.6782	6.0484
3	Orange peel	36.974	4.3725	5.966	0.602	52.0855	15.3035
4	Tamarind bark	38.336	3.7254	5.055	0.938	51.9456	21.3035
5	Bamboo	37.947	2.5417	5.789	0.140	53.5823	15.6613
6	Locust bean pod	26.076	6.0182	4.438	0.518	62.9498	36.2230
7	Deleb palm nut husk	22.379	2.9461	4.055	0.238	70.3819	15.8105
8	Palm Kernel Shells	25.298	5.6151	4.614	0.252	64.2209	41.1165
9	Wild coffee plant	35.028	3.4109	3.820	0.882	56.8591	12.2864
10	Bambara groundnut shell	30.941	3.4108	3.291	0.756	61.6012	17.9380

11	African mahogany	32.304	3.4672	2.998	0.280	60.9508	18.4374
12	Gmelina bark	33.082	3.2534	4.114	0.406	59.1446	25.9424
13	Soybean stalks	16.152	2.1089	6.847	0.700	74.1921	5.3353
14	Guinea Corn Husks	30.425	3.9822	0.108	0.881	64.6038	15.9955
15	Wheat Husks	60.501	5.2780	1.329	0.987	31.905	17.8251
16	Corn cobs	51.252	4.8375	0.021	1.782	42.1075	19.2349
17	Groundnut shells	55.412	4.1473	0.014	0.881	39.5457	18.7362
18	Rice Husks	64.505	3.7821	0.015	2.104	29.5939	9.4034
19	Sawdust	45.126	4.6315	0.024	0.701	49.5175	18.7495
20	Maize husks	75.982	3.3869	0.1256	1.0783	19.4272	20.0748

Comparison between measured and computed energy values

The energy values of biomass fuels are most precisely measured using a bomb calorimeter as defined for example in the British Standard methods (BS: 1016: part 5:1977), American Standard of Testing Materials (ASTM E711-87) and can be estimated from the empirical correlations for example Equations 2 and 3. Figure 1 shows a direct comparison between the calorific values of bomb measurements and those estimated using the two correlation equations by Boei (1953) and Tillman (1978). The data indicates that the bomb measurements do not excellently agree with the values estimated using correlation equations. In most of the data points, the bomb measurement is higher than that estimated using such equations. The analysis indicates that about 60% of the data points computed using the two equations agree closely. Bomb data are considered to be more reliable and accurate in the present study since most data from this machine are in good agreement with widely reported calorific values of biomass in the range of 15-21 MJ/kg. The correlation equations underpredict the calorific values for a number of data points with seven data points for Tillman (1978) accounting for 35% that closely matched the experimental results. The underprediction might be due to assumptions used in modelling the equations and therefore need further revision to accurately predict the experimental data measured with the bomb. The Boie equation is derived based on the properties of hydrocarbon fuels and has a prediction for biomass materials that lie at 1.8%. The Tillman equation is based on the assumption that the heating value of biomass is a function of its carbon contents only and has a correlation found to have a prediction within 5% (Channiwala and Parikh, 2002).

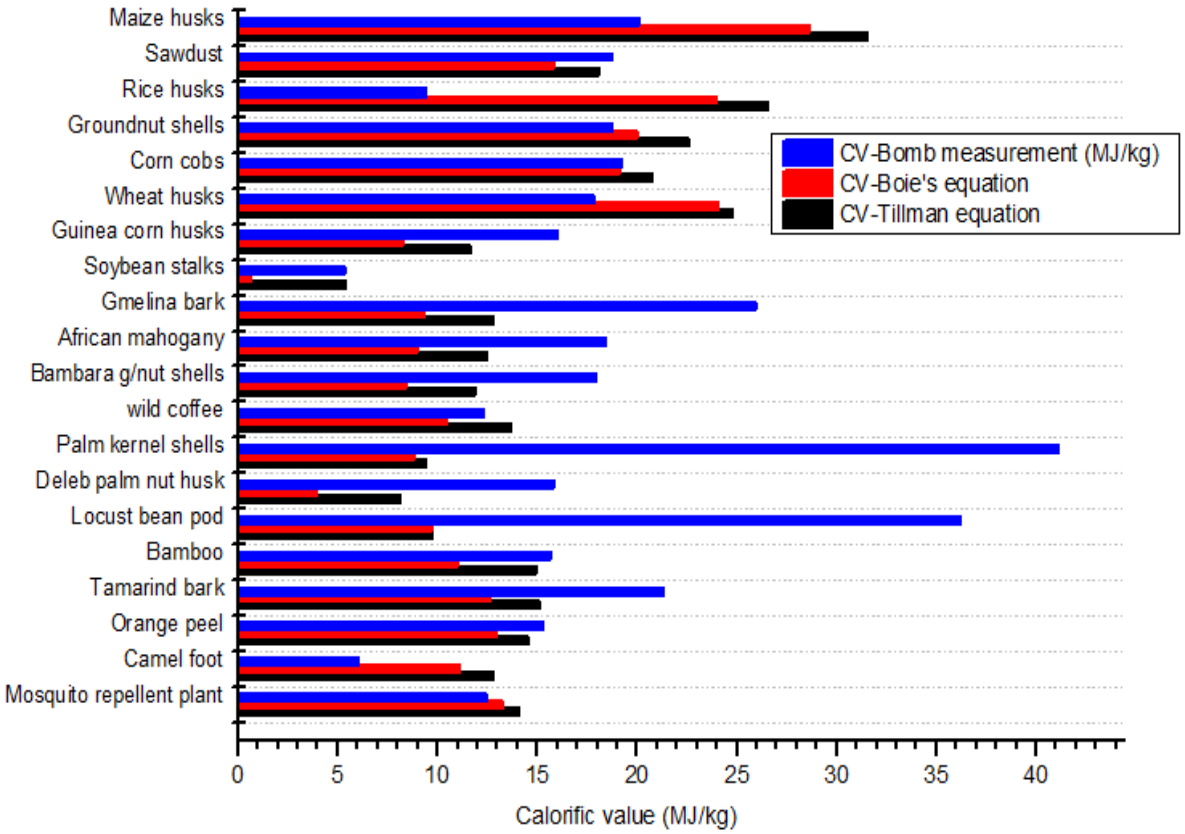

Figure 1: Comparison of measured and computed calorific values of the biomass samples

Relationship between the total carbon and hydrogen contents of biomass

Figures 2.0 and 3.0 depict a graph of calorific value as a function of total carbon and hydrogen contents of biomass samples. From the trend of data shown in the two graphs, it is evident that the calorific values of most biomass are linearly related to their total carbon content and have no direct relationship to their total hydrogen values. This means that the higher the percentage of the carbon content of the sample, the higher the energy value to do useful work. A similar finding

was reported by Ismaila, *et al* (2013). The correlation coefficient R^2 for calorific values as a function of carbon and hydrogen contents were calculated as 1 and -0.03978 respectively. The R-value shows that there is a positive and direct relationship between the calorific value and the percentage carbon values of plant biomass. This finding agrees closely with the theoretical formulations by Tillman (1978), Channiwala and Parikh (2001) and Yin (2011). These empirical equations indicate that the heating value of plant biomass has a very strong relationship to its fixed carbon content. The fixed carbon content represents the amount of combustible matter present in the char residue after loss of volatile matter and moisture. It should be noted here that both moisture and ash contents of the sample may significantly affect its heating or calorific value. In addition, the higher oxygen content of biomass material also reduces its calorific value due to increased oxidation. It should be emphasised here that the carbon and oxygen contents are important in biomass energy analysis. Higher carbon content tends to form high-grade biomass fuel as shown in our data and higher oxygen content tends to lower the calorific value. Figure 2 shows that higher carbon contents contribute positively to the calorific value of all the samples. Considering the total carbon data in Table 1 and the Tillman energy graph shown in Figure 1, it can be seen that maize husk with a total carbon value of 75.982 (wt%) has the highest computed energy value of 35.5569 MJ/kg while soybeans stalk with 16.152 (wt%) has the least energy value of 5.3932 MJ/kg. On the other hand, soybean stalk with the highest oxygen content of 74.1921 (wt%) has the lowest energy value and maize husk with the lowest oxygen value of (19.4272 (wt%) has the highest energy value. This means that higher oxygen value tends to reduce the heating value due to increased oxidation during combustion and it is, therefore, important in biomass conversion routes to de-oxidize the plant biomass fuel in order to increase the calorific value.

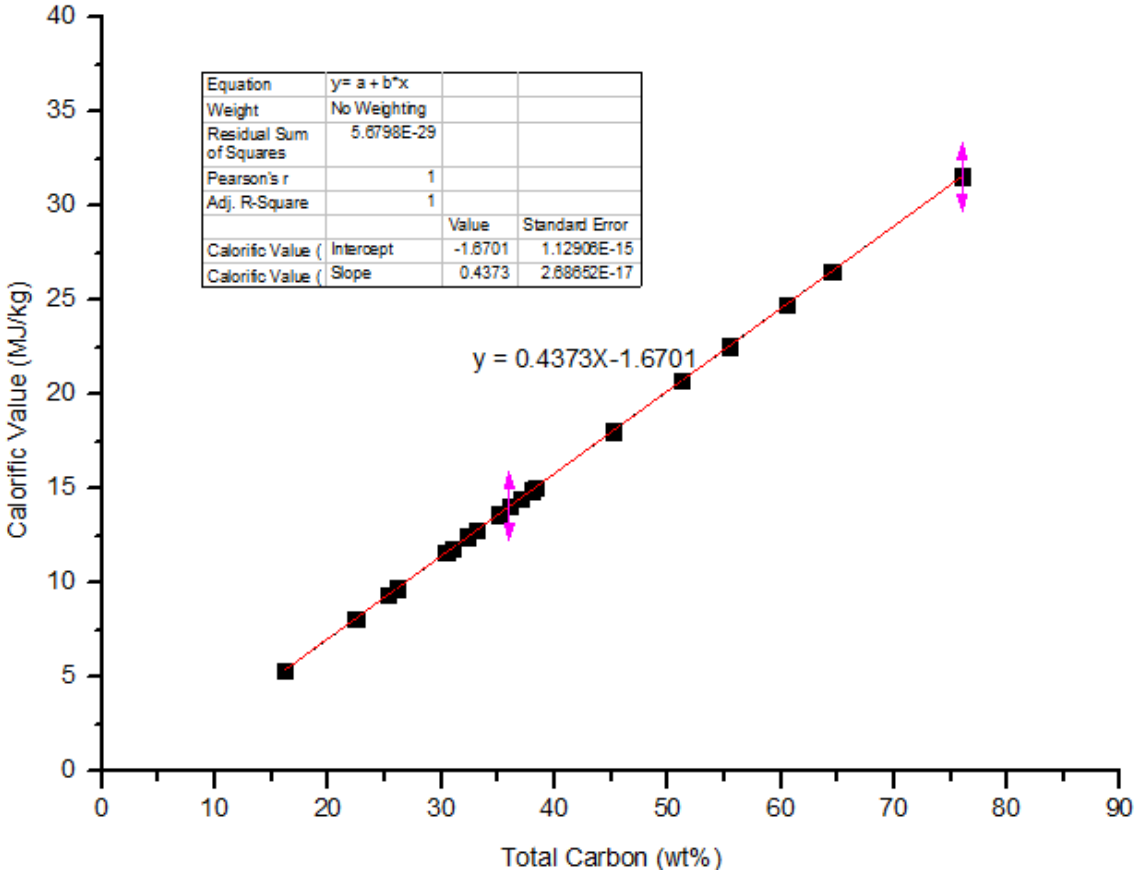

Figure 2: A graph of calorific value as a function of total carbon content of biomass samples

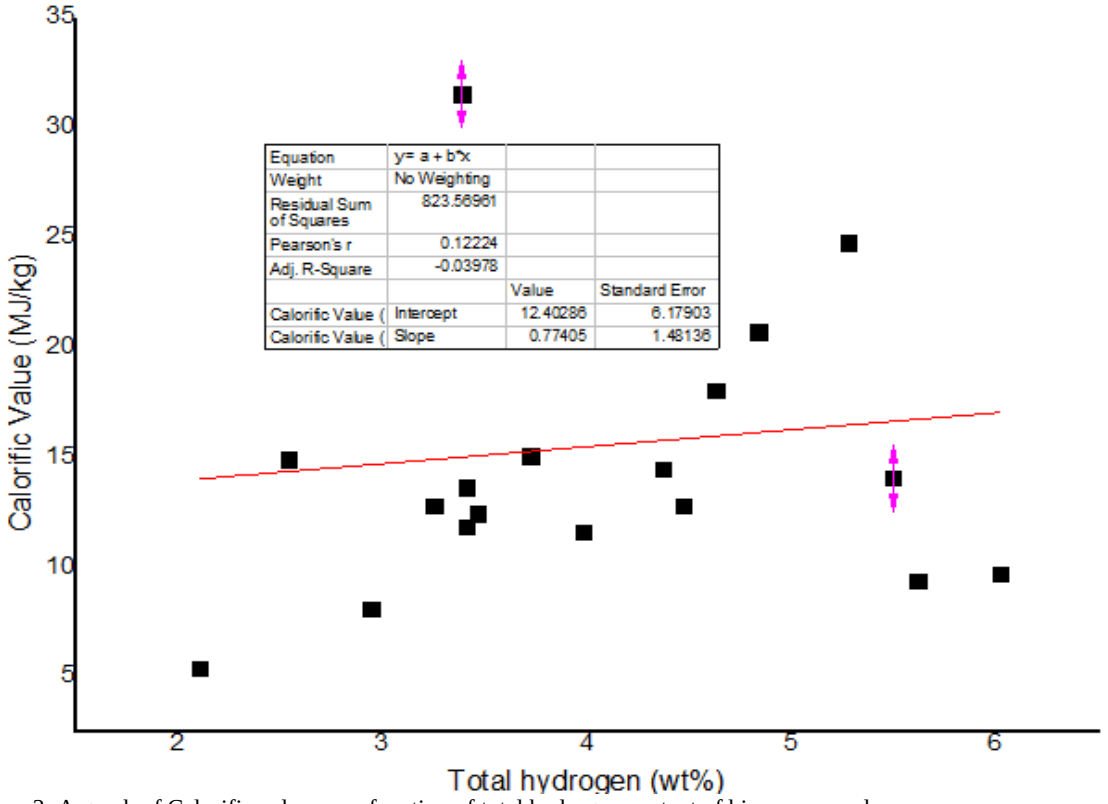

Figure 3: A graph of Calorific values as a function of total hydrogen content of biomass samples

CONCLUSION

The heat energy values of 20 selected plant biomass are determined using bomb calorimeter and estimated from the correlation equations developed by Boie (1953) and Tillman (1978). The relationship between the energy value and total carbon and hydrogen contents were analysed. Comparisons between the experimental data measured with the bomb machine and computed data were made to estimate the prediction capabilities of the two correlation equations. This work has clearly shown that, the experimental results indicates that palm kernel shell and locust bean pod have the highest energy values of 41.1165 MJ/kg and 36.2230 MJ/kg followed by Gmelina bark and Tamarind bark with energy values of 25.9424 MJ/kg and 21.3035 MJ/kg respectively. Camel foot and soya bean stalks have the lowest energy values of 6.0484 MJ/kg and 5.3353 MJ/kg respectively. Also, the energy values of about 60% of biomass samples are in the range of 15-21 MJ/kg in agreement with the literature and ASTM standard measurements. Lastly, the energy values measured with the bomb are slightly higher than those computed using correlation equations. However, about 60% of the data points computed using the two equations agree closely. Bomb data are considered to be more accurate in the present study. The analysis shows that the calorific values of biomass samples are strongly related to their total carbon contents and weakly related to their total hydrogen contents. The authors recommends that the calorific values of other plant biomass should be determined to understand their potential to add to energy mix for domestic and small-scale industrial heating applications.

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