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An Overview of the Biomass Torrefaction Technology and Characterization of Solid Waste Fuels

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Abstract Torrefaction has been shown to increase the energy density, stability, and handling properties of biomass, making it a more suitable feedstock for use in power generation and other applications. This paper reviewed the torrefaction of biomass solid waste and its energy content using ultimate, proximate, calorific value, and volatile matter content analyses to check biomass-specific compositions. The diverse biomass feedstocks are agricultural residues, forestry residues, energy crops, leaves, fruit wastes, and sewage sludge. Biomass torrefaction approaches and torrefied solid fuels were discussed with their essential constituents. Torrefied products were characterized using torrefaction principles and mathematical modelling to estimate the exact quantity and quality. The significance of machine learning approaches to predicting energy content was stated. The bulk density content of the torrefied biomass is increased with an increment in torrefaction temperature, resulting in an increase in the porosity property modelling, thereby improving its grindability status and energy content. Machine learning algorithms served as predictive models for the quality of the torrefied biomass. It provides valuable insights into the accuracy and efficiency of trusted techniques for predicting energy contents and their potential for industrial applications.

Keywords: Biomass, Energy content, Fuel quality, Torrefied, Solid waste

I. Introduction

Over time, the use of fossil fuels has amplified social, environmental, and climate change problems due to the emission of contaminants into the atmosphere, such as carbon dioxide, sulphur, and nitrogen oxide. Therefore, biomass is one of the most appealing and popular renewable energy sources due to its low sulphur content and carbon dioxide neutrality properties [1]. As a result of biomass carbon-neutral possession and generation sustainably, biomass is quickly becoming a key part of the energy mix. This has unarguably shifted the world away from using fossil fuels for a more environmentally friendly energy source.

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from plants and animals. There are different sources of biomass: agriculture, forest, municipal (food waste, waste paper), and biological (animal waste, aquatic species). Agricultural by-products are good raw materials for biochar manufacturing and effective waste management options due to their abundance and availability. More work and innovation are ongoing to make it a more accessible, less expensive alternative, and a valuable replacement for conventional electricity and other energy sources. It can be burned directly to provide heat, turned directly into electricity, or processed into biofuel [2].

II. Biomass Solid Waste

Biomass is defined as organic materials derived from plants and animals. When biomass is used for the production of biofuel, the biofuel is often classified as first-generation or second-generation. The first-generation biofuels are derived from food or oil crops. Examples include ethanol, which is sourced from starch (in crops such as wheat and corn/maize) and sucrose (in crops such as sugar beet and sugarcane). Second-generation biofuels are sourced from lignocellulosic biomass. The most prevalent type of biomass is lignocellulosic, which comprises a wide range of biomass types such as grasses, wood, energy crops, and municipal and agricultural wastes [3].

Raw biomass material can be used as a fuel, but there are a number of drawbacks, including its huge bulk volume, high moisture content, and relatively low calorific value, which makes it a costly fuel to transport. This problem is acute when biomass is to be used in pulverized systems, such as cofiring with coal in large-scale utility boilers. All of these drawbacks have given rise to the development of new technologies in order to increase the quality of biomass fuels. One way to deal with some of these difficulties is to produce densified pellets from biomass. The following methods can use biomass to create energy [4].

i. Thermochemical (combustion, gasification)

ii. Biological (anaerobic digestion, fermentation)

iii. Chemical processes (esterification).

The untreated biomass has the drawbacks as follows [5]:

i. low energy density
ii. Compound with high moisture and oxygen content
iii. Hygroscopic behaviour,
iv. Poor grindability.

This untreated biomass is subjected to a variety of analyses to check for specific components. These analyses are listed below [6]:

i. Ultimate Analysis: An elemental analyzer measures the raw and torrefied carbon, hydrogen, nitrogen, and sulphur contents.
ii. Calorific Value Analysis: The bomb calorimeter determines the calorific value (HHV) of raw and torrefied PKS.
iii. Proximate Analysis: Proximate analysis consists of determining the ash content, moisture content, volatile matter, and fixed carbon.
iv. Volatile matter content: Volatile matter is a measure of the nonwatery gases generated during the heating of a coal sample.

a. Essential components of biomass

Figure 1 shows the various low-molecular-weight substances and macromolecular-weight substances available in biomass. Biomass materials are essentially a composite of carbohydrate polymers with a small amount of inorganic matter and low-molecular-weight extractable organic constituents [6].

Cellulose is a high-molecular-weight polymer that makes up the fibers in wood and other biomass. This strength is important in cell walls, where the microfibrils are meshed into a carbohydrate matrix, conferring rigidity to plant cells. Cellulose degradation begins at 240–350 °C, resulting in anhydrous cellulose and levoglucosan. The crystalline structure resists thermal depolymerization better than unstructured hemicelluloses. Amorphous regions in the cellulose contain waters of hydration and hold free water within the plant. When heated rapidly, this water is converted to steam, which can rupture the cellulose structure.

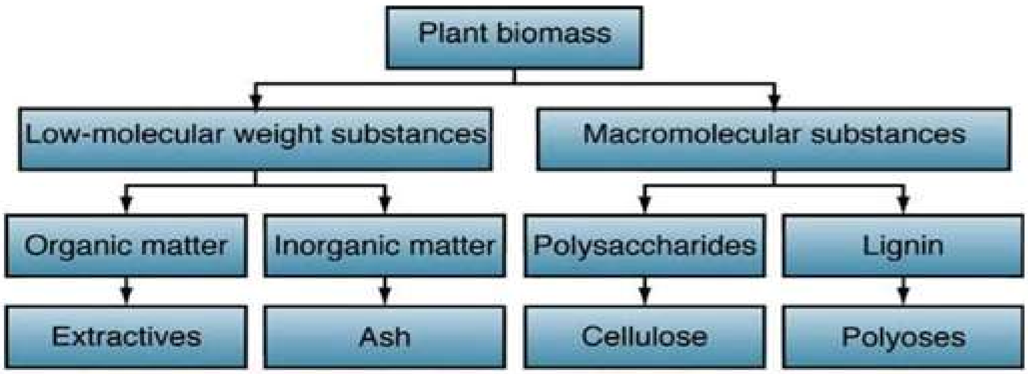

Figure 1. Plant biomass composition [6]

The hemicelluloses are branched polymers consisting of shorter chains: 500–3000 sugar units as opposed to the 7,000–15,000 glucose molecules per polymer seen in cellulose. Hemicellulose thermal degradation occurs with slow pyrolysis in the range of 130–260 °C, with the majority of weight loss occurring above 180°C depending on its chemical nature and relationship with lignins within the cell. It evolves as light volatiles, producing fewer tars and char compared to cellulose [7].

b. Biomass reaction

Polysaccharides are arranged in long chains called microfibrils enclosed in even structures of amorphous lignin, building the core of the crystalline cellulose. The cellulose is encased in a shell of hemicellulose. All these building blocks are more or less influenced by heat, but in different temperature ranges; therefore, they are converted by specific reactions. Biomass torrefaction has been recognized as a technically feasible method for converting raw biomass into a high-energy-density, hydrophobic, compactable, grindable, and lower oxygen-to-carbon ratio solid that is suitable for commercial and residential combustion and gasification applications. The raw biomass contains appreciable amounts of oxygen, nitrogen, sulphur, chlorine, and fluorine, which makes it thermally unstable and produces tars and oils that can be problematic in conventional equipment used for coal combustion or gasification. The relatively high oxygen-to-carbon ratio in biomass can have advantages and disadvantages. The high oxygen content can be used to form a stoichiometric ratio of H_2 and CO to produce synthetic fuels and chemicals [8].

III. Torrefaction Technology

One of the ways of achieving this biomass thermal conversion objective is through the application of the torrefaction process. Torrefaction is a promising technology for the production of bioenergy from lignocellulosic biomass. By removing moisture, volatile organic compounds, and other impurities, torrefaction is a technological advancement aimed at increasing the energy density and stability of biomass, making it more appropriate for use as a fuel in power production and other uses. The process involves heating the biomass in a limited oxygen environment, resulting in the production of a solid, energy-dense product with improved fuel properties. This thermal technique is used to turn diverse streams of woody biomass or agricultural waste into high-quality solid biofuel. The outcome is a solid biofuel that is stable, homogenous, and of the highest quality. It has a higher energy density and calorific value than the original feedstock [8]-[9].

The design of a torrefaction reactor is important for optimizing the process for maximum energy output and improved fuel properties. There is a growing interest in predicting the energy content of torrefied biomass products based on their respective proximate and ultimate analysis data. The accurate measurement of the heating value of torrefied biomass is essential for proper utilization in industrial applications [10]. The bomb calorimeter widely used for measuring the heating value of torrefied biomass is time-consuming and expensive. An alternative approach is to predict the heating value from the proximate and ultimate analysis of the torrefied biomass using statistical and artificial intelligence techniques. This process of predicting the biomass heating value can be used to optimize the torrefaction process and improve the fuel properties of the torrefied biomass [11].

a. Torrefaction principles

Torrefaction is a partially controlled and isothermal pyrolysis of biomass occurring in a temperature range of 200–300 ºC. Carbonization of biomass using torrefaction can be good for reducing moisture content and increasing calorific value, which makes biomass energy dense. Torrefaction is a feasible method for improving the properties of biomass as a fuel. The treatment yields a solid, uniform product with a lower moisture content and a higher energy content compared to raw biomass. Most of the bound water is removed by a thermo-condensation process, which occurs above 160°C when the formation of CO_2 begins. Further heating between 180 and 270 °C results in an exothermic reaction and initiates the decomposition of the hemicellulose, which causes the biomass to change color due to the loss of water, CO_2, and large amounts of acetic acid and phenols. The energy values of these compounds are relatively low, resulting in a significant increase in the energy density of the biomass. The process becomes completely exothermic at temperatures greater than 280°C, resulting in significant increases in the production of CO_2, phenols, acetic acid, and other higher hydrocarbons. The torrefaction process, when carried out at temperatures less than 250°C, is generally endothermic and may decrease its energy efficiency. However, some of the studies carried out on system energy balances and economics indicate that torrefied biomass could be a viable option for co-gasification of combustion with coal [12].

b. Pyrolysis of Biomass

Pyrolysis is the thermal decomposition of material occurring in the absence of oxygen, which includes the first steps in the combustion and gasification processes that are followed by partial or total oxidation of the primary products. Lower process temperatures and longer vapor residence times favour the production of charcoal (upper end of the torrefaction process), whereas higher temperatures and longer vapor residence times increase gas production (lower end of the gasification process). Moderate temperatures and short vapor residence times are optimum for producing liquids (pyrolysis range) [12].

c. Torrefied products

The prediction of the heating value of torrefied biomass from its proximate and ultimate analysis is an important research area, as it can provide a quick and cost-effective means for determining the quality of torrefied biomass. This would, in a small measure, help industries that use torrefied biomass as a fuel source optimize their processes and ensure a consistent and reliable fuel supply. Machine Learning Models such as artificial neural networks, random forest, and linear regression have been used to establish relationships between the proximate analysis data (such as moisture content, ash content, and volatile matter) and the ultimate analysis data in predicting the heating value of the torrefied biomass. Machine learning techniques such as artificial neural networks, random forests, and linear regression have shown great promise in predicting the heating value of biomass from its proximate and ultimate analysis [13].

i. The proximate analysis of biomass involves determining its major components, such as moisture, volatile matter, fixed carbon, and ash content.
ii. Ultimate analysis determines the elemental composition of biomass, including carbon, hydrogen, nitrogen, sulphur, and oxygen.
iii. Artificial neural networks are mathematical and machine learning techniques that can be used to develop predictive models for torrefaction [14].
iv. Random forest can be applied in the torrefaction of biomass to predict the properties and characteristics of the torrefied biomass based on input variables such as heating time, temperature, and feedstock type.

Artificial neural networks can be used to develop models that predict the quality of the torrefied biomass based on the proximate analysis results, allowing for the optimization of the process parameters and the reduction of energy consumption during torrefaction. Random forest can be applied in the torrefaction of biomass to predict the properties and characteristics of the torrefied biomass based on input variables such as heating time, temperature, and feedstock type. With the application of historical data on the torrefaction process and its outcomes, a random forest model can be trained to make predictions on new data and optimize the torrefaction process for desired outcomes. The use of machine learning algorithms such as random forest, artificial neural networks, and linear regression in the prediction of the energy content of torrefied biomass can help to improve the efficiency and effectiveness of the biomass torrefaction process, leading to more sustainable and cost-effective fuel sources. Torrefaction technology is a promising method to reprocess low-quality biomass into high-energy-density feedstock. Despite the benefits of torrefaction, the current reactor design principles require adjustment to enhance the efficiency and productivity of the process. Moreover, the evaluation of energy content in the torrefied biomass has traditionally relied on the use of proximate and ultimate analyses, which are time-consuming and costly. There is a need for a more efficient and cost-effective method for quantifying the energy content of the torrefied biomass [15].

d. Importance of torrefaction

Torrefaction is a process that effectively lowers the oxygen and carbon ratios of biomass. The energy consumption during milling is reduced, and at the same time, sharp edges and splinters are eliminated in the milled powder, greatly enhancing feeding properties. The torrefied biomass has also proved to have hydrophobic properties, which gives it an advantage in long-term storage compared to raw biomass. Torrefaction, also referred to as mild pyrolysis, occurs before the pyrolysis process on a continuum of temperatures, starting at drying and ending at gasification. Torrefaction Process

Technique [16]. The thermochemical process of torrefaction is actually an incomplete pyrolysis process and is characterized by the following parameters: reaction temperature 200–300°C, heating rate less than 50°C/min, absence of oxygen, residence time lower than 30 minutes at a temperature greater than 200°C, ambient pressure, and flexible feedstock. The absence of oxygen in the reactor is of great importance to avoid oxidation and ignition. Torrefied biomass in general defines a group of products resulting from the partially controlled and isothermal pyrolysis of biomass occurring in a temperature range of 200–230 ºC and 270–280 ºC. During the initial heating, drying takes place, which is followed by further heating during which more water is removed due to chemical reactions through a thermo-condensation process. This happens at over 160 °C and also results in the formation of CO_2. Between 180 and 270 °C, the reaction is more exothermic, and the degradation of hemicellulose continues. Moreso, there are many advantages to the pretreatment of biomass using torrefaction before densification. Torrefaction reduces variability in the feedstock, which is mainly due to differences in types of raw materials, tree species, climatic and seasonal variations, storage conditions, and time, and helps in developing a uniform feedstock to produce high-quality densified biomass [17].

Besides improving physical attributes, torrefaction also results in a significant change in the proximate and ultimate composition of the biomass, making it more suitable for fuel applications. An increase in torrefaction temperature results in an increase in carbon content and a decrease in hydrogen and oxygen content due to the formation of water, carbon monoxide, and carbon dioxide. This process also causes the hydrogen to carbon ratio and oxygen to carbon ratio to decrease with increasing torrefaction temperature and time, which is favourable because it results in less smoke and less water- vapor formation and reduced energy loss during combustion and gasification processes [18].

Characteristics of biomass by the torrefaction process will decrease the water content, reduced oxygen content, and hemicellulose content. The nature of the biomass makes it difficult to absorb water, thus increasing the energy content. Under the torrefaction process, the characteristics of biomass will be close to those of coal [19]. In general, the torrefaction was a mild pyrolysis process with the occurrence of a reaction in series and continued with heat and mass transfer. Degradation of components of the biomass has become more intense at temperatures above 200 ºC by starting with decreasing hemicellulose components. During torrefaction, the colour of biomass becomes darker. The factors that affect the quality of the product of the torrefaction process of biomass are the biomass size, temperature, torrefaction reactor, and residence time within the reactor. The longer torrefaction process can cause a loss of energy from biomass components that will decrease energy content [20]-[21]. The conditions of biomass feedstock and the torrefaction process affected the quality of products of such calorific value. Biomass with a high content of hemicellulose will be difficult to change its characteristics through the torrefaction process because the content of hemicellulose is the component that opens pores in biomass and closes them again. The temperature of the torrefaction process also affected the quality of biomass products. The temperature of the torrefaction process below 200 ºC will produce a high ability to absorb water due to the hemicellulose that did not degrade at that temperature. Then, the temperature of torrefaction above 300 ºC will produce a lower energy product due to some parts of the combustible gas being volatile matter carried by the flow of gas. Temperature was instrumental in removing the hemicellulose content that will change the characteristics of biomass and make it difficult to absorb water. Properties of a torrefied product. Torrefaction of biomass significantly changes physical properties like moisture content, density, grindability, pelletability, hydrophobicity, and calorific value, as well as storage behaviours in terms of off-gassing, spontaneous combustion, and self-heating [22].

IV. Properties of Torrefied Products

a. Moisture content

The amount of moisture in a fuel is a crucial characteristic since a fuel with more moisture loses more energy during burning. Biomass with less moisture is more stable during storage and has a lower risk of biological degradation [23].

b. Density

Mass loss in the form of solids, liquids, and gases during the torrefaction process causes the biomass to become more porous. This results in a significant reduction in volumetric density, typically between 180 and 300 kg/m^3, depending on the initial biomass density and torrefaction conditions [24].

c. Grindability

Grindability is estimated by the amount of energy utilized in the process of grinding. The lower the energy required, the higher the grindability. Raw biomass has a high fiber content and hard ground as a result of these fibers linking to one another. The changed characteristics of biomass fibers, which result in lower fiber toughness and increased brittleness, account for the improved grindability of torrefied biomass [25].

d. Hydrophobicity

Water binds to the surface of biomass pores in lignocellulosic biomass through hydrogen bonding to the hydroxyl groups in the cell wall. The hydrogen in the water molecule connects to the oxygen in the hydroxyl group in the cell wall. The higher the oxygen content of the cell wall, the greater the probability of hydrogen bond formation [26].

e. Pelletability

Variability in feedstock quality due to differences in the types of raw materials, tree species, climatic and seasonal variations, storage conditions, and time significantly influences the quality of biopellets. Torrefying the biomass before pelletization produces uniform feedstock with consistent quality. Lignin in the biomass is considered the basic binding agent; thus, the pelletability of any biomass is evaluated based on the amount of lignin. In general, the higher the amount of lignin, the better the binding and the milder the process conditions required for densification. Woody biomass has more lignin than lignocellulosic biomass and binds easily. The torrefaction process opens up more lignin-active sites by breaking down the hemicellulose matrix and forming fatty, unsaturated structures, which create better binding [27].

f. Calorific value

Biomass loses relatively more oxygen and hydrogen than carbon during torrefaction, which in turn increases the calorific value of the product. The mass and energy in the torrefied biomass are predominantly preserved in the solid product for a long time, as the material does not degrade with time [28].

V. Machine Learning Approaches

Data-driven machine learning has been shown to provide improved accuracy in predicting higher heating values for different types of biomass materials. Comparing with empirical models, machine learning methods provide improved accuracy and are used to estimate the relative contribution of each input variable to the predicted higher heating values (HHV). HHV provides an indication of biomass quality as it defines the optimum energy recovery potential of the biomass. Compared to the lower heating value (LHV), the HHV includes the latent heat of the evaporation of water in the fuel and the products of the reaction. The HHV values of biomass can be experimentally measured with an adiabatic oxygen bomb calorimeter [29].

VI. Determination of Torrefied biomass Contents

The percentage of moisture content (Mc) in biomass is determined by equation 1.

$$Mc = \frac{m_1 - m_2}{m_1}\ x\ 100 \qquad (1)$$

where: m_1 is the weight of specimen and m_2 is the weight of specimen after drying in moisture test.

The biomass volatile matter (Vm) percentage is found by equation 2

$$Vm = \frac{m_2 - m_3}{m_1}\ x\ 100 \qquad (2)$$

Where m_1 is the weight of specimen used, m_2 is the weight of specimen after drying in moisture test and m_3 is the weight of specimen after drying in muffle furnace.

The ash content is found by using equation 3.

$$Ac = \frac{W_b - W_e}{W_b}\ x\ 100 \qquad (3)$$

Where: W_b is weight of biomass sample and W_e is weight of empty crucible

The percentage fixed carbon content (Fcc) is estimated as contained in 4

$$\mathrm{Fcc} = 100 - (\mathrm{Mc} + \mathrm{Ac} + \mathrm{Vm}) \qquad (4)$$

The percentage of crude protein content present in the product is found by equation 5.

$$Cp = \frac{V_2 - V_1 \times C_A \times 0.0014 \times 100 X\ 6.25}{W_3 \times 10} \times 100 \qquad (5)$$

where V_1 is the volume of blank, V_2 is the volume of the sample, C_A is the concentration of the acid and W_3 is the weight of biomass.

The percentage crude fibre of each of the samples is analysed using equation (6)

$$Cf = \frac{W_2 - W_3}{W_2 - W_1} \times 100 \qquad (6)$$

where W_1 is the weight of empty crucible, W_2 is the weight of empty crucible + sample, and W_3 is the weight of empty crucible + ash biomass.

The percentage of weight of fat (Fc) collected is expressed in equation (7)

$$Fc = \frac{W_2 - W_3}{W_3 - W_1} \times 100\% \qquad (7)$$

In Equation (7), W_1 is the weight of the thimble, W_2 is the weight of the thimble + the sample, and W_3 is the weight of the defatted sample + the thimble (after drying).

The carbohydrate percentage of the product is calculated as contained in (8).

$$\mathrm{Ch} = 100 - (\mathrm{Mc} + \mathrm{Fc} + \mathrm{Cp} + \mathrm{Cf}) \qquad (8)$$

a. Determination of mass yield and energy yield of biomass solid fuels

The percentages per torrefied mass yield (My) and energy yields (Ey) is calculated by using equations 9 and 10.

$$\mathrm{My} = \frac{M_t}{M_u} \times 100 \qquad (9)$$

$$\mathrm{Ey} = \frac{M_y\ x\ H_{vt}}{H_{vu}} \qquad (10)$$

Where H_{vt} is the HHV of untorrefied, M_t is the mass of torrefied, M_u is the mass of untorrefied and H_{vt} is the HHV of torrefied.

VII. Torrefied Biomass Characterization

The torrefied biomass is characterized by fuel properties and energy content determined using proximate, ultimate and elemental analyses [30]. The proximate analysis of biomass gives moisture content, volatile matter, ash content. The moisture content is found by equation 11.

$$Mc = \frac{W_2 - W_3}{W_2 - W_1} \times 100\% \quad (11)$$

where: W_1 is the mass of the petridish, W_2 is the mass of the petridish with the sample and W_3 is the mass of the petridish with the sample after being heated and cooled.

The volatile matter (Vm) is determined by equation 12

$$Vm = \frac{W_6 - W_4}{W_5 - W_4} \times 100\% \quad (12)$$

where: W_4 is the mass of the crucible, W_5 is the mass of the crucible with sample, W_6 is the mass of the crucible with sample after being heated in the muffle furnace and cooled in the desiccator

The ash content (Ac) of the bio-char is determined using the relation 13.

$$Ac = \frac{W_8 - W_4}{W_7 - W_4} \times 100\% \quad (13)$$

where: W_4 is the mass of the crucible, W_7 is the mass of the crucible with sample, W_8 is the mass of the crucible with sample after being heated in the muffle furnace and cooled in the desiccator.

The fixed carbon of the torrefied biomass is estimated by equation 14.

$$\mathrm{FC} = 100 - (\mathrm{MC} + \mathrm{VM} + \mathrm{ASH}) \quad (14)$$

VIII. Elemental Analysis of Biomass

The biomass sample elemental analysis involves the determination of the percentage of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) [31].

The carbon and hydrogen contents in percentages are found by equations 15 and 16

$$\mathrm{C} = \frac{12Y}{44x} \times 100 \quad (15)$$

$$\mathrm{H} = \frac{2Y}{18X} \times 100 \quad (16)$$

The nitrogen content of biomass in percentage is calculated as follows:

$$N = \frac{NVa}{Ws} \times 100 \quad (17)$$

Va is volume of acid used, N is normality and Ws is sample weight

Equation 18 is employed to calculate the percentage of sulphur in the samples.

$$\mathrm{S} = \frac{RVD}{Ws} \times 100 \quad (18)$$

where: V is total volume and D is the dilution factor

The percentage of hydrogen and oxygen in the biomass is obtained indirectly using equation 19.

$$(H + O) = 100 - (C + N + S) \quad (19)$$

The calorific energy value for biomass is calculated using the equation 20

$$\frac{H}{M} = (m_w C_w + Q_c)\Delta T \quad (20)$$

Where: H is the heat energy absorbed (J), ΔT is the change in temperature (°C), M is the mass of biomass, m is the mass of water (g), Q_c is the heat energy for vessel and C_w is the specific heat capacity for water.

The bulk density (B) for biomass is found by equation 21.

$$B = \frac{Ws}{V} \quad (21)$$

IX. Conclusions

The paper reviewed the torrefaction of biomass solid waste and its energy content to enhance solid fuel quality. The products of the torrefaction process were assayed for their compositions, contents, and characteristics. The overview established the possibility of using solid fuel as an alternative source of energy and provided valuable insights into the use of torrefaction technology for improving the properties of biomass for energy production. The energy of the torrefied biomass is found to be higher than the non-torrefied biomass, thus the energy densification of the torrefied. The bulk density of the examined biomass increases with an increase in torrefaction temperature, resulting in an increase in torrefied product porosity and improving their grindability and energy content. The elemental composition of the torrefied biomass increases with an increase in the torrefaction temperature and residence time. A constant and low nitrogen content and negligible low sulphur content for torrefied products increase.

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