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Research article

Combustion Enhancement of Torrefied Agricultural Waste Briquettes: Effects of Temperature, Time and Binder Ratios

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ABSTRACT

This study investigated the enhancement of combustion properties in briquettes produced from torrefied agricultural wastes (rice husk, sawdust, and maize cob) by analyzing the effects of torrefaction temperature, duration, and binder ratio. The torrefaction behavior was examined at temperatures ranging from 200°C to 300°C and durations from 10 to 60 minutes under an inert nitrogen atmosphere. The torrefied samples were characterized, and briquettes were produced. Results indicated that sawdust was the most efficient feedstock due to its low ash content (2.5%) and high carbon content (50%). The optimal torrefaction conditions were 240°C–260°C for 30–40 minutes. A binder-to-material ratio of 1:5 yielded briquettes with the highest heating value (18,716 kJ/kg) and material strength. The study concluded that torrefaction and binder optimization significantly enhanced the combustion properties of agricultural waste briquettes.

1. INTRODUCTION

Alongside the persistent rise in global population and the unchecked escalation of energy costs, carbon-offset initiatives designed to mitigate greenhouse gas (GHG) emissions have been the central focus of apprehensions regarding global warming, forecast global energy consumption to reach 400 exajoules annually, with an anticipated growth of fifty percent by 2025 [1]. The increasing global population has led to a heightened need for energy, primarily crude oil, in a manner that is less sustainable [2]. The significant political instability in oil-exporting countries is elevating oil prices and complicating market forecasts, this has been a catalyst for the increasing demand for clean and sustainable energy sources [3]. In 2005, Europe instituted a cap-and-trade system that limits carbon dioxide emissions from approximately fifty percent of the industrial sector to comply with the emission targets established by the Kyoto Protocol [4]. Moreover, fossil fuels comprising coal, natural gas, and petroleum significantly contribute to global warming, and it might be contended that their reserves are depleting, moreover, their emissions are detrimental not only to the environment but also to human health, as per (IPCC, global carbon utilization leads to emissions of around 7 billion tonnes year, with projections indicating a rise to 14 billion tonnes per annum by 2050 [5]. To mitigate greenhouse gas emissions, nations importing heavy crude oil, such as the United States, China, and the European Union, are diligently seeking sustainable alternative energy sources to decrease their emissions, consequently, bioenergy, derived from biomass, is a crucial renewable energy source that numerous industrialized nations, including Canada, have identified as significantly reducing greenhouse gas emissions and substantially contributing to sustainable energy production. Similar to fossil fuels, bioenergy can exist in various forms, including solid (bio-solids), liquid (bio-oil/ethanol), or gas (bio-gas), and can be distributed to multiple locations [6, 7]. The capacity to cultivate crops specifically engineered for energy production is substantial, with bioenergy constituting ten percent of the global energy supply derived from neglected agricultural and forest waste [8].

The proportion of biomass energy utilized for energy generation remains minimal relative to the global total energy production, this is despite biomass energy's significant rise in popularity in recent years, this may stem from various factors, one of which pertains to the constraints associated with its characteristics [9]. The variations in the characteristics of biomass feedstock in its original state provide several challenges in the processes of handling, shipping, grinding, and combusting or co-firing with coal [10]. Biomass in its unprocessed form exhibits the following attributes low heating value, high moisture content, significant smoke production during combustion, low combustion efficiency, poor grindability, high ash content, low energy density, and elevated hygroscopicity [11]. The torrefaction method, a thermal treatment of biomass, has been shown to enhance the combustible properties of biomass.

Hemicellulose, cellulose, and lignin are the three principal polymer components of biomass. During torrefaction, these polymers undergo depolymerisation; the depolymerisation of lignin and cellulose is generally mild, whereas that of hemicellulose is pronounced [12]. Consequently, biomass retains most of its energy content even after undergoing torrefaction . Moreover, the torrefaction product exhibits an elevated carbon content (a diminished hydrogen-to-carbon ratio), an increased calorific value, and a superior energy density [13].

A briquette is a densified block of flammable biomass, including sawdust, maize cobs, and rice husks, briquettes serve as a biofuel substitute for coal and charcoal, typically utilized as a solid fuel source. Solid fuel is a tangible material utilized for energy production, often combusted in a fire. This can act as an alternative to fossil fuel utilization [14].

Biomass originally denoted the total mass of living stuff inside a specific unit of ecological space. Recently, the phrase has been applied to plant material, vegetation, or agricultural waste utilized as an energy source, characterized biomass materials as composites of carbohydrate polymers with low molecular weight, minimal inorganic content, and extractable organic constituents [15]. Biomass is characterized as a biological or organic material capable of serving as a renewable energy source via thermal or biochemical conversion methods [16]. Biomass, comprising organic materials and all living organisms, contains energy taken from the sun and stored as chemical energy, this chemical energy is subsequently converted into thermal energy through numerous transformation mechanisms, crops, grasses, wood remnants, wood waste, agricultural byproducts, animal waste, and municipal garbage are all examples of many elements that can be categorized as biomass [17].

Biomass, unlike fossil fuels, is a renewable energy source that can be renewed and has the potential to yield zero net greenhouse gas emissions, wood wastes serve as a prime illustration of this phenomenon, representing byproducts derived from forestry operations, the process of photosynthesis entails trees receiving sunlight and carbon dioxide from the atmosphere to synthesize cellulose from carbohydrates [18]. Consequently, cellulose, which harbors stored chemical energy, emits this energy as heat upon combustion, and the volume of carbon dioxide released as off-gas is roughly proportional to the amount absorbed during photosynthesis, consequently, biomass possesses the potential to be devoid of greenhouse gas emissions [19].

Properties of Biomass

The efficacy of biomass as a fuel depends on its source and kind, which are defined by the biomass's physical and chemical properties, the physical characteristics of biomass encompass its dimensions, shapes, specific heat capacity, thermal conductivity, moisture content, bulk density, grindability, and porosity [20]. The chemical characteristics of biomass are evaluated using ultimate or proximate analysis, the elemental composition of biomass, as determined by final analysis, includes carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), chlorine (Cl), and ash components such as potassium (K), these values are shown as a percentage of the total biomass weight [21]. The proximate analysis provides the percentage composition of fixed carbon (FC), moisture (M), ash (A), and volatile matter (VM) in the biomass, the chemical and physical properties may change based on temperature and the duration of biomass exposure. Cellulose, hemicelluloses, lignin, and various chemical compounds influence the combustion process of biomass materials [22]. Also, the concentration of each component varies according to the species, type of plant tissue, growth stage, and developmental conditions of the plant [23].

Overview of Torrefaction

The application of biomass in thermal conversion processes to produce consumable fuels, such as coal, is limited by the inherent physical and chemical properties of biomass, torrefaction is a thermal pretreatment process that enhances the combustion properties of biomass, making them equal to those of coal [24]. Research has shown that various types of biomass, together with their sources and characteristics, exhibit unique responses to thermal treatment, the initiation of the thermal degradation process of biomass depends on the specific type of biomass [25]. Torrefaction is a process that leads to the degradation or depolymerization of biomass, this process yields various volatiles, culminating in a solid fuel known as torrefied biomass or torrefied fuel, in the 1930s in France, research on the production of torrefied wood (TW) for gasifiers introduced the notion of torrefaction related to wood pretreatment [26].

Mechanism of Torrefaction

The torrefaction process induces thermal decomposition of biomass, resulting in various reactions within its polymeric and cellular structure, delivered an exhaustive account of the decomposition process, decomposition occurs in the hemicellulose structure by limited devolatilization and carbonization when the torrefaction temperature is low [27]. A slight breakdown occurred in the lignin and cellulose structure, nonetheless, only a negligible degree of devolatilization and carbonization occurred inside the structure of lignin and cellulose [28]. This contrasts with the considerable heat degradation that transpires in hemicellulose at temperatures ranging from 200 to 300 degrees Celsius, consequently, one can conclude that hemicellulose is the most reactive polymer component of biomass, which may be associated with the significant mass loss observed in biomass during the torrefaction process [29].

Main Properties of Torrefied Biomass

Torrefaction treatment significantly enhances the combustibility of biomass by altering its physical and chemical properties, a process whose outcomes are contingent upon both the initial biomass properties and the key operational parameters of temperature and residence time [30]. These improvements are demonstrated through a higher heating value and increased energy density escalating with elevated temperatures and prolonged times due to moisture reduction and a higher carbon-to-oxygen ratio resulting in a product that retains over 90% of its energy for only 70% of its original mass for a roughly 30% gain in energy density [31]; furthermore, the process bestows hydrophobic characteristics from the degradation of O-H bonds, preventing moisture absorption, and creates a more brittle material with enhanced grindability that requires considerably less energy to pulverize [32].

Energy Requirements for Torrefaction

The energy requirements for the torrefaction process can be categorized into three phases of reactions. The steps are dictated by the characteristics of the biomass (sawdust, rice husk, and maize cob) and the conditions in which the process occurs [33]. As the initial phase of the process is the drying stage, encompassing the preliminary heating and pre-drying operations [34]. To achieve the vaporization of the biomass, the temperature is often around 110 degrees Celsius at this stage, the moisture will persist in evaporating until the critical moisture content is reached, at which juncture the rate of evaporation will begin to diminish significantly [35]. The breakdown of biomass typically commences at approximately 180 degrees Celsius, as the temperature of the solid biomass rises, the heat front persists in advancing within the biomass [25]. The principal degradation reaction induced by this impact is endothermic, at around 250 degrees Celsius, the degradation process of woody biomass becomes exothermic [34]; nevertheless, this is insignificant compared to the endothermic reaction occurring below 300 degrees Celsius due to insufficient char and gas production, the figure below illustrates that a substantial quantity of energy (or heat duty) is necessary throughout the pre-drying and post-drying phases, chiefly due to moisture removal and the biomass attaining its ignition temperature, Conversely, the torrefaction process necessitates a markedly reduced quantity of energy [36].

Biomass Briquette

Biomass briquettes are engineered blocks of condensed organic material, primarily manufactured from agricultural and forestry byproducts such as sawdust, rice husk, and maize cobs, which serve as a renewable and economically viable alternative to traditional fossil fuels like coal and oil for industrial boiler applications [37]. The advanced production process of torrefaction a thermo-chemical treatment that roasts the biomass in a low-oxygen environment fundamentally enhances the fuel's properties, resulting in torrefied briquettes (or biocoal) that boast a significantly higher calorific value, improved water resistance, and superior grindability, which collectively can reduce boiler fuel costs by 30-40% [38, 39]. This innovation not only provides a sustainable waste management solution by recycling refuse into energy through waste briquetting but also generates valuable carbon credits for industries due to the net reduction in atmospheric greenhouse gas emissions, making it a cornerstone of long-term green energy strategies in both developed nations like Canada and developing regions such as southern India [40, 41].

2. MATERIALS AND METHOD

The under listed materials and apparatus were used in the course of the experiment and served as the basis for the development of torrefied biomass briquette.

Materials and Apparatus

The following materials and apparatus, in the specified quantities, were utilized for the experimental procedure: one, 15kg of saw dust; two, 15kg of maize cob; three, 15kg of rice husk; four, a calorimeter with burner; five, a weighing balance; six, muffle furnaces; seven, a Kjehdal nitrogen regulator; eight, binder; nine, a muffle oven; and ten, a hand press hydraulic compressor, which was used to produce 2 briquettes.

Sample Preparation

Sawdust (from the sawmill), rice husk (from Onyx rice mill), and maize cob prepared to particle size between 2mm, were. All the biomass samples were dried in an open area for 10 days before being stored at room temperature on site, using air tight containers, to provide a basis for experiments, Briquettes were produced and tested using eight different binder-to-material ratios: 1:1, 1:2, 1:3, 1:4, 1:5, 1:6, 2:1, and 2:3.

Biomass Pre-Treatment by Torrefaction

The torrefaction behavior of the three kinds of raw materials, sawdust and rice husk, and maize cob was investigated under six different temperature levels of 200ºC, 220ºC, 240ºC, 260ºC, 280ºC, and 300ºC at varying time interval of 10, 20, 30, 40, 50 and 60minutes respectively. The temperature was controlled by a digital controller system. The temperature was set at 210, 250, 290ºC. If the temperature is lower or higher than the desired temperature of 10ºC, the heater will work or be shut down, automatically. In each run, two (2) kilograms of sawdust, rice husk or maize cob was subject to torrefaction (atmospheric press) at six different temperature severities 200ºC, 220ºC, 240ºC, 260ºC, 280ºC, and 300ºC for 1hour. A muffle oven modified to accommodate a gas inlet and outlet, fitted with a one way valve system was used, the torrefaction process was carried out in an inert atmosphere using nitrogen gas, at aconstant flow rate of 50 l/h. A high gas flow rate was used to ensure a constant gas flush, prior to commencing the torrefaction process, the system was purged for 20 minutes to remove air from the oven, the oven was then heated at a heating rate of 10ºC/min to the desired torrefaction temperature, this temperature was then held for 1 hour before being turned off, then the unit was allowed to cool under the same gas flow rate conditions to approximately 100ºC. Then the samples were transferred to a desiccator and cooled to the room temperature. Once cooled, the treated sample was weighed and characterized. Schematic diagram of the torrefaction unit shown schematically in Figure 1 to ensure uniform results, the torrefaction process was repeated twice and average values were taken.

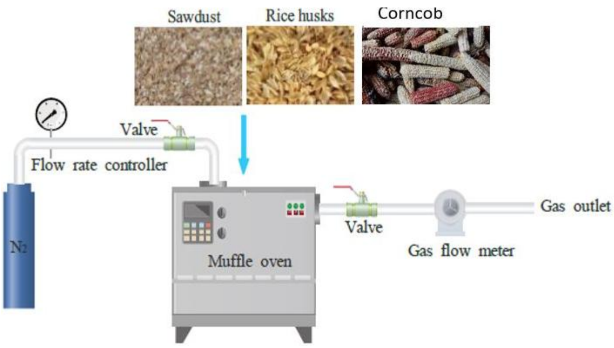

Fig. 1. Schematic diagram of the torrefaction unit.

Characterization and Measurement

Methodology for Proximate Analysis of Biomass

Sample Preparation

The biomass sample (e.g., wood chips, agricultural residue, energy crops) was initially air-dried to remove superficial moisture. The air-dried sample was ground using a rotary mill and sieved to achieve a homogeneous particle size of ≤ 250 μm (passing through a 60-mesh sieve). The prepared sample was stored in an airtight container at room temperature to prevent moisture absorption prior to analysis.

Determination of Moisture Content (ASTM E871 / ISO 18134)

The moisture content was determined by measuring the mass loss upon heating the sample under specified conditions. A clean, dry moisture dish was heated in an oven at 105°C for 1 hour, cooled in a desiccator, and weighed (W_1), approximately 1 gram (W_2) of the prepared sample was placed in the dish and spread evenly, the dish containing the sample was placed in a mechanical convection oven and dried at 105 ± 2°C for a minimum of 4 hours or until constant mass was achieved. the dish was then transferred to a desiccator to cool to room temperature and reweighed (W_3).

$$\text{Moisture Content (\%, wet basis)} = [(W_2 - W_3) / (W_2 - W_1)] \times 100. \quad (1)$$

Where:

W_1 = mass of empty dish (g), W_2 = mass of dish + sample before drying (g), W_3 = mass of dish + sample after drying (g).

Determination of Ash Content (ASTM D1102 / ISO 18122)

The ash content was determined as the inorganic residue remaining after combustion of the sample at a high temperature. A porcelain crucible was ignited in a muffle furnace at 575°C for 30 minutes, cooled in a desiccator, and weighed (W_4), approximately 1-2 grams (W_5) of the dried sample (from Section 2.0) was placed in the crucible, the crucible was placed in a cold muffle furnace, the temperature was gradually increased to 575 ± 25°C and maintained for a minimum of 4 hours, or until constant mass was achieved, to ensure complete combustion of all carbon, the crucible was cooled in a desiccator and weighed (W_6).

$$\text{Ash Content (\% dry basis)} = [(W_6 - W_4) / (W_5)] \times 100. \quad (2)$$

Where:
W_4 = mass of empty crucible (g), W_5 = mass of dry sample (g), W_6 = mass of crucible + ash after combustion (g).

Determination of Volatile Matter (ASTM E872 / ISO 18123)

Volatile matter was determined as the fraction of the sample, excluding moisture, that was released as gas at high temperature under specific conditions in the absence of air. A covered platinum crucible was ignited at 950°C, cooled in a desiccator, and weighed (W_7).approximately 1 gram (W_8) of the dried sample was placed in the crucible, the lid was firmly closed, the crucible was placed directly into a pre-heated muffle furnace at 950 ± 20°C and held for exactly 7 minutes, the crucible was removed from the furnace, cooled in a desiccator, and reweighed (W_9).

$$\text{Volatile Matter (\% dry basis)} = \{[(W_8 + W_7) - W_9] / W_8\} \times 100 - \text{Moisture Content (\%)} \quad (3)$$

Calculation of Fixed Carbon

Fixed carbon was calculated as the solid combustible residue that remained after the volatile matter was driven off.
$$\text{Fixed Carbon (\% , dry basis)} = 100\% - [\text{Ash(\% , db)} + \text{Volatile Matter(\% , db)}] \quad (4)$$

Ultimate Analysis of Biomass

Ultimate analysis determined the elemental composition of a biomass sample on a dry basis, quantifying the major organic elements: carbon (C), hydrogen (H), nitrogen (N), and sulfur (S). The oxygen (O) content was calculated by difference. The analysis was performed using a dedicated elemental analyzer based on the principle of complete combustion of the sample and subsequent separation and detection of the resulting gases.

Instrumentation

The analysis was conducted using a [Perkin Elmer] CHNS/O Elemental Analyzer. The instrument was equipped with a dynamic flash combustion system (operating at 900-1000°C), a chromatographic column for gas separation, and a thermal conductivity detector (TCD) for precise quantification of eluted gases.

3. RESULTS AND DISCUSSION

Proximate Analysis

Ash Content Analysis

After torrefaction as shown in figure 2 rice husk exhibited the highest ash content at over 9%, indicating a significant amount of inorganic material that may affect combustion efficiency and require additional ash management; maize cob, with an ash content of 8.5%, similarly poses combustion challenges, while sawdust, with the lowest ash content at approximately 2.5%, stands out as the most efficient feedstock for energy conversion, reducing concerns related to ash handling and maintenance.

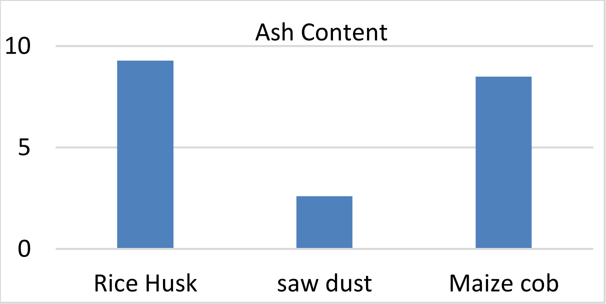

Fig. 2. Percentage ash content after torrefaction.

Volatile Matter Analysis

After torrefaction as shown in figure 3 sawdust retained the highest volatile matter content at 72%, making it the most efficient feedstock for combustion due to enhanced ignition and flame propagation, while rice husk, with 67% volatile matter, remains moderately reactive but may produce higher emissions, and maize cob, with the lowest volatile matter content of 65%, shows reduced combustion efficiency and requires optimized burning conditions, highlighting that torrefaction reduces moisture and volatiles, leaving sawdust as the best option for efficient energy recovery compared to rice husk and maize cob.

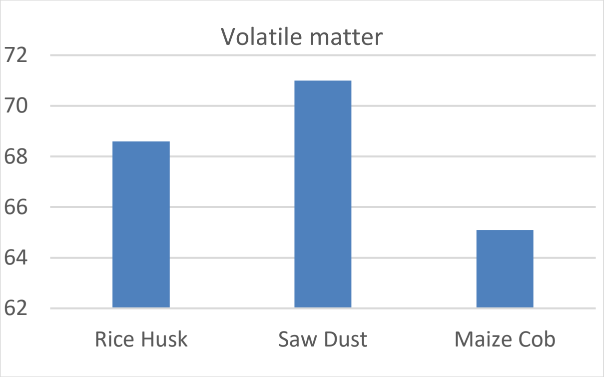

Fig. 3. Percentage volatile matter after torrefication.

Fixed Carbon Analysis

After torrefaction as shown in figure 4, rice husk had the lowest fixed carbon content at 18%, indicating lower energy density and efficiency for long-duration combustion, while sawdust (21%) and maize cob (21.5%) show higher fixed carbon levels, making them better suited for sustained combustion and energy applications; this suggests that sawdust and maize cob retain more solid combustibles post-torrefaction, whereas rice husk may offer shorter combustion periods and lower energy density.

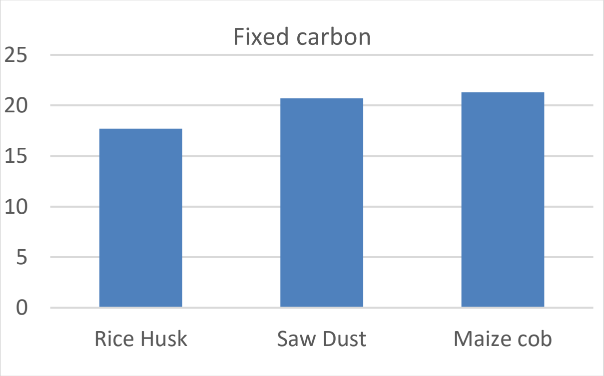

Fig. 4. Percentage fixed carbon after torrefaction.

Moisture Content Analysis

In figure 5. the bar chart compared the moisture content for rice husk, saw dust, and maize cob, showing that rice husk has the lowest moisture content at approximately 4.5 units, saw dust has the highest at around 6 units, and maize cob falls in between at slightly above 4.5 units, with this information being useful for determining the suitability of these materials for specific applications, such as bioenergy production, where moisture content impacts combustion efficiency or drying processes.

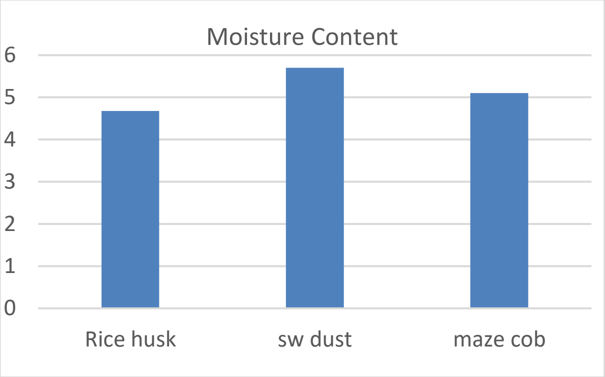

Fig. 5. Percentage moisture content after torrefaction.

Ultimate Analysis Measurement

In figure 6. the bar chart showed the ultimate analysis results for Rice Husk, Saw Dust, and Maize Cob, showing the composition of Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), and Sulfur (S), where Saw Dust has the highest carbon content (50%) and moderate oxygen levels, making it the most energy-dense fuel, Rice Husk has a balanced composition with the highest hydrogen content, moderate carbon content (48%), and notable sulfur (0.5%), while Maize Cob, with the highest oxygen content (50%), low sulfur, and nitrogen levels, is environmentally favorable but less energy-efficient, ultimately indicating Saw Dust as the most promising material for energy generation, followed by Rice Husk and Maize Cob.

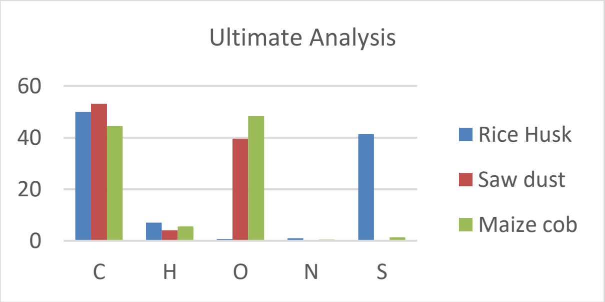

Fig. 6. Ultimate analysis of the elemental composition.

Percentage Weight Loss of Rice Husk Characteristics

In figure 7 the bar chart showed the percentage weight loss (wt%) of rice husk at various temperatures (200°C, 220°C, 240°C, 260°C, 280°C, and 300°C) over different time intervals (10, 20, 30, 40, 50, and 60 minutes), where weight loss is minimal and slow at 200°C (25-35%) and slightly higher at 220°C (25-35%), becomes more significant at 240°C (30-40%) with a peak at 30 minutes, reaches its maximum at 260°C (40% at 10 minutes) indicating rapid thermal breakdown, increases gradually to 40% at 280°C but at a slower rate, and stabilizes at 300°C (20-30%), highlighting that weight loss accelerates with temperature, peaks around 260^{0}C-280°C due to rapid decomposition, and stabilizes as the material approaches full degradation.

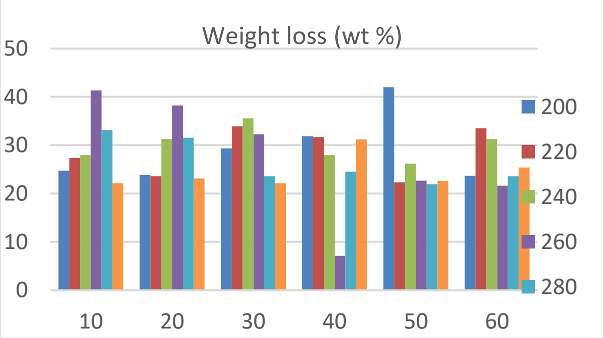

Fig. 7. Percentage weight loss of rice husk at different temperature.

Percentage Weight Loss of Saw Dust Characteristics

In figure 8 weight loss of sawdust increases with temperature, indicating greater thermal degradation at higher temperatures, with fluctuations across time intervals; at lower temperatures (200–240°C), weight loss remains moderate and gradual, suggesting slower decomposition, while at higher temperatures (260–300°C), weight loss becomes more pronounced, particularly at 40 and 50 minutes where 260°C exhibits a peak (35%), indicating substantial biomass decomposition, after which the trend stabilizes or decreases beyond 50 minutes, highlighting 260°C as an optimal temperature for thermal breakdown and emphasizing the need for precise control of residence time to achieve desired

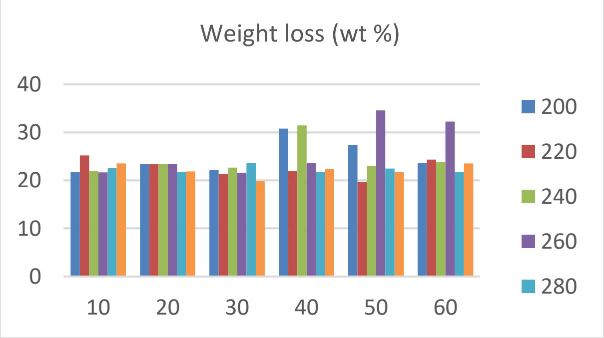

Fig. 8. Percentage weight loss of saw dust at different temperature.

Percentage Weight Loss of Maize Cob Characteristics

In figure 9 the percentage weight loss of maize cob at varying temperatures (200°C–300°C) and time intervals (10–60 minutes), showed a general trend where weight loss fluctuated slightly but remained within a narrow range (20–24%), with lower temperatures (200^{0}C–240°C) exhibiting consistent and limited degradation, higher temperatures (260^{0}C–300^{0}C) showing only slight increases, particularly at early time intervals like 10 minutes, and overall revealing that thermal decomposition occurs predominantly early in the process with minimal influence from extended residence times, highlighting a stable decomposition pattern across temperatures and a moderate impact of temperature and time on maize cob weight loss.

Fig. 9. Percentage weight loss of maize cob at different temperature.

High Heating Value Measurement

The bar chart in Figure 10 illustrateed the high heating values (HHV) of briquettes at various binding ratios, showing that calorific values fluctuate with the binder ratio, where 1:3, 1:4, and 1:5 exhibit the highest values (18,500 kJ/kg) due to optimized combustion efficiency, while 1:2 and 2:1 yield the lowest (16,500 and 15,000 kJ/kg) because excessive or insufficient binder reduces performance, and intermediate values (17,000 kJ/kg) occur at 1:1 and 2:3, highlighting the importance of binder optimization for maximizing energy content.

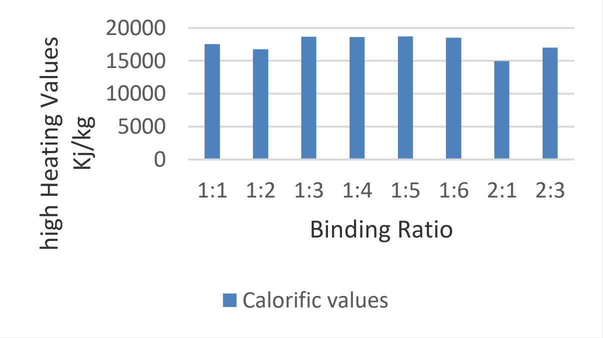

Fig. 10. High heating values of the briquette at different binding ratio.

Material Strength Analysis

From the result obtained as shown in figure 11 briquets at 240^{0}C, with respect to time at 30 to 40 mins. The briquet produced the best heating value as compared with the other material at corresponding temperature and time interval. From binder 1:1 to 1:4 in this format, the binding ratio of the binder increases and decreases with respect to the ratio of the binder to material but the binding of ratio (1:50 gave the best heating value from the result obtained corresponding to 18716kj/kg with a material strength of 1216.4kg/g.

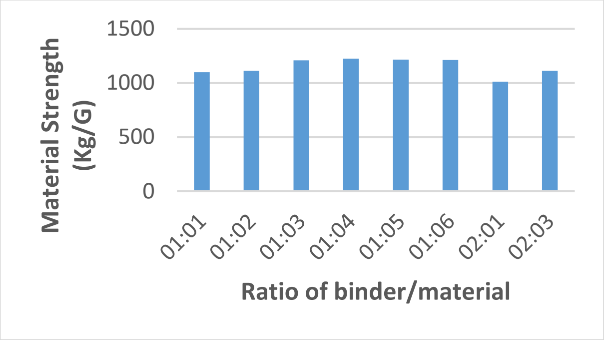

Fig. 11. Material strength of the briquette at different binding ratio.

Surface Morphology Analysis

Figure 12 showed the observations of raw material and torrefied biomass at the torrefaction temperatures of 200^{0}C, 220^{0}C, 240^{0}C, 260^{0}C, 280^{0}C and 300^{0}C. It can be seen from figure 10 that with the increased torrefaction temperature and resident time of one (1) hour, the color of sawdust, rice husk and maize cob changed from light yellow to dark brown, due to the carbonization of the biomass surface. Maize cob was more sensitive to the increasing temperature, especially at the torrefaction temperatures of 240-260^{0}C, where the color of the torrefied maize cob was significantly darker than that of the torrefied sawdust and rice husk. The difference in surface breakdown between sawdust, maize cob and rice husk may be attributed to the different hemicellulose contents in the two materials. For biomass sample in the torrefaction temperature range of 200^{0}C–300^{0}C, mass loss is dominated by dehydration and de-volatization in the reaction regime of hemicellulose component. When the temperature increased, volatiles were released and a deposit was formed on the solid surface partially because of the rapid formation of blockage.

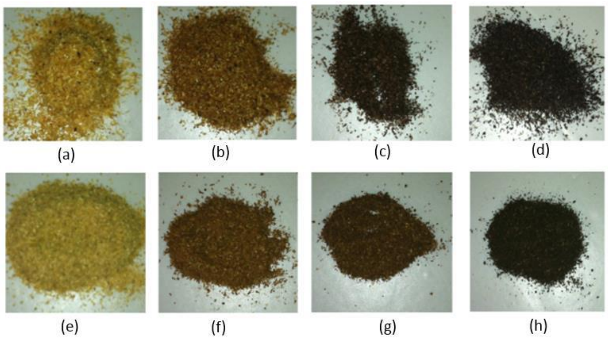

Fig. 12. Observations of Raw Material and Torrefied Biomass at the Torrefaction Temperatures of 200^{0}C, 220^{0}C, 240^{0}C, 260^{0}C, 280^{0}C and 300^{0}C.

Discussion of Result

The results of this study demonstrated that torrefaction conditions (temperature and residence time) and binder-to-material ratios exerted a significant influence on the physicochemical and combustion properties of briquettes produced from rice husk, sawdust, and maize cob, as reflected in proximate and ultimate analyses where sawdust exhibited the most favorable characteristics with the lowest ash content (2.5%), highest volatile matter (72%), and highest carbon fraction (50%), thereby ensuring superior ignition and sustained combustion compared to rice husk, which although moderately rich in carbon (48%) and hydrogen, suffered from high ash (>9%) and notable sulfur (0.5%) that could impair efficiency and increase gaseous emissions, and maize cob which, despite its moderate fixed carbon (21.5%), demonstrated limited reactivity and lower energy yield due to high oxygen content (50%); thermal decomposition trends further confirmed that sawdust and rice husk achieved maximum weight loss at 260–280°C with stabilization beyond this point, whereas maize cob showed only minor degradation across all conditions, highlighting structural rigidity; collectively these findings established the torrefaction window of 240–260°C for 30–40 minutes as optimal for maximizing energy density while minimizing energy losses, and combustion performance tests revealed that binder optimization was equally critical, with a 1:5 binder-to-material ratio producing briquettes of the highest heating value (~18,716 kJ/kg) and greatest mechanical durability (1216.4 kg/g), outperforming lower or excessive binder ratios that compromised cohesion or diluted energy content; surface morphology analysis corroborated these observations by showing progressive carbonization with temperature increases, with maize cob being more temperature-sensitive due to higher hemicellulose degradation, and together these results demonstrate that sawdust-based briquettes produced under optimized torrefaction and binder conditions represent the most energy-efficient, durable, and environmentally favorable biomass option, while rice husk requires emission controls due to high ash and sulfur, and maize cob may be better suited for blending strategies to improve combustion efficiency.

4 CONCLUSION

The findings of this study demonstrated that the combustion properties of briquettes made from torrefied agricultural wastes can be significantly enhanced through optimal control of torrefaction temperature, duration, and binder ratio, with sawdust proving to be the most efficient feedstock due to its low ash content (2.5%), high volatile matter (72%), and high carbon content (50%), while rice husk presents challenges with its highest ash content (9%) and lowest fixed carbon (18%), and maize cob offers moderate combustion efficiency, with the most effective torrefaction temperatures for all feedstocks being 240°C–260°C at 30–40 minutes, a 1:5 binder-to-material ratio yielding the highest heating value (18,716 kJ/kg) and good mechanical strength (1,216.4 kg/g) and torrefaction-induced color changes in surface morphology, particularly in maize cob, attributed to variations in hemicellulose content, with sawdust emerging as the most promising biomass for briquette production when optimized for maximum energy output and structural integrity.

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