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Research Article

Investigation of sustainable utilization of agricultural waste through coffee husk and cow dung briquettes for domestic energy production and emission performance

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Abstract

The widespread use of traditional biomass fuels like firewood and charcoal in developing countries contributes to deforestation, indoor air pollution, and energy insecurity. Agricultural residues such as coffee husks offer a renewable alternative, but their direct utilization is limited by low bulk density and poor combustion efficiency. This study developed and characterized coffee husk briquettes using cow dung as a natural binder in varying proportions (0%, 10%, 20%, 30%). Briquettes were evaluated for physicochemical, thermal, chemical, and emission properties according to ASTM standards. Key results showed moisture content of 4.40–5.60 wt.%, volatile matter of 67.83–69.84 wt.%, ash content of 8.96–14.76 wt.%, and density ranging from 730.7 to 1042 kg/m³. Compressive strength varied from 2.749 to 3.679 MPa, with higher and lower heating values between 18.31–22.06 MJ/kg and 14.36–16.49 MJ/kg, respectively. Specific fuel consumption ranged from 0.10605 to 0.13665 kg/L. Emission levels of NOx and SO_2 ranged from 8.2–17.69 PPM and 170.99–201.32 PPM, respectively, within standards. The findings confirm that coffee husk briquettes with cow dung binder are a viable, sustainable energy option, suitable for rural and coffee-producing regions.

1.0 Introduction

The world is currently facing a dual challenge of meeting growing energy demands while mitigating the negative environmental impacts of conventional fossil fuels [1,2]. Fossil fuels such as coal, petroleum, and natural gas have long been the dominant sources of energy, but their extraction and use have led to severe environmental consequences, including greenhouse gas (GHG) emissions, global warming, and air pollution [3–5]. As a result, the search for alternative, sustainable, and renewable energy sources have intensified globally. Biomass energy, derived from organic matter, is a leading candidate in this transition due to its renewability, carbon neutrality, and local availability, especially in rural and agricultural communities [6–8]. To frame the present work, the discussion focuses on biomass options relevant to rural contexts.

In developing countries, especially in Sub-Saharan Africa and parts of Asia, a significant portion of the population relies on traditional biomass fuels such as firewood, charcoal, and crop residues for cooking and heating [9–11]. While these fuels are accessible, their usage is inefficient and associated with health and environmental hazards [9–11]. The combustion of firewood and charcoal in poorly ventilated spaces results in indoor air pollution, contributing to respiratory diseases [12,13]. Addressing this exposure is essential for cleaner household energy transitions.

Moreover, the widespread use of these traditional fuels contributes to deforestation and land degradation. These challenges underscore the need to explore more efficient and environmentally friendly forms of biomass energy [8,14–16]. Reducing pressure on forest resources is therefore a parallel priority to reducing indoor emissions.

Among the many biomass resources available, agricultural residues are increasingly being recognized for their energy potential [17,18]. One such residue is coffee husk, a by-product generated during the processing of coffee beans. Coffee is a globally significant commodity and a vital export product for many developing countries, particularly in Africa and Latin America. In Uganda, for example, coffee remains a top agricultural export, with the processing of beans generating vast quantities of husks. Unfortunately, these husks are often disposed of through open dumping or burning, leading to environmental pollution and waste of valuable biomass [19,20]. Valorizing this waste stream can simultaneously reduce pollution and supply local fuels.

Coffee husks possess characteristics that make them suitable for bioenergy applications [21]. They have a reasonable calorific value, are widely available in coffee-producing regions, and are generally underutilized [21,22]. However, the direct use of coffee husks as a fuel source presents certain limitations. They typically exhibit low bulk density, high moisture content, and poor combustion efficiency, which reduces their practicality as a direct fuel [21,22]. These drawbacks necessitate a densification process such as briquetting, which can enhance their fuel characteristics by increasing energy density, reducing storage and transportation issues, and improving combustion behavior. In this context, densification offers a practical pathway from residue to usable household fuel.

Briquetting is a mechanical process in which loose biomass materials are compressed into solid blocks or logs, often with the aid of binders to improve cohesion and structural stability [23,24]. The process not only improves the handling properties of biomass but also facilitates more efficient combustion [22,25]. Numerous studies have demonstrated the benefits of briquetting various biomass residues, including sawdust, rice husks, groundnut shells, and wheat straw. However, studies focusing on coffee husks as a feedstock for briquetting remain limited. This motivates testing coffee husks with suitable binders.

The selection of an appropriate binder is crucial in briquette production, as it affects the durability, mechanical strength, and combustion characteristics of the final product [23,26,27]. Natural binders such as starch, molasses, and clay have been used, but cow dung has emerged as a particularly attractive option, especially in rural settings [27,28]. Cow dung is readily available, cost-effective, and possesses inherent binding properties. Moreover, it contributes to the calorific value of the briquettes and assists in the uniform burning of the fuel. Leveraging locally available binders can also lower production costs and enhance adoption.

Studies have explored the use of cow dung as a binder for biomass briquettes. For instance, Anatasya et al., [29] reported that cow dung improved the compressive strength and calorific value of briquettes made from agricultural waste. Patil et al., [30] demonstrated that cow dung-bonded briquettes outperformed those using other binders such as wheat flour and paper pulp in terms of combustion efficiency and mechanical integrity. Despite this promising evidence, limited research has specifically addressed the use of coffee husks in combination with cow dung for briquette production. Existing literature has primarily focused on the agricultural applications of coffee husks, such as their use as compost or animal feed. Their potential as a renewable energy source, especially when enhanced through briquetting with effective binders like cow dung, remains underexplored. This gap in knowledge presents an opportunity to evaluate the feasibility of producing high-quality briquettes from coffee husks and cow dung, thereby contributing to sustainable energy development and waste management. Accordingly, this study targets the coffee-husk–cow-dung system.

Moreover, the practical benefits of using such briquettes extend beyond energy generation. By converting agricultural waste into fuel, this approach supports Circular Economy (CE) principles and reduces the environmental burden associated with open dumping and burning. It also aligns with the United Nations Sustainable Development Goals (SDGs), particularly those related to affordable and clean energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13). Crucially, improved briquettes can expand access to clean, affordable cooking energy in underserved communities.

The motivation for this study is rooted in the need to develop locally available, sustainable energy alternatives that address the dual challenges of waste management and energy poverty in rural communities. In many developing nations, access to reliable and affordable energy remains a major obstacle to socioeconomic development. By utilizing locally sourced biomass residues and binders, communities can produce clean and efficient cooking fuel, reduce dependence on forest-based energy sources, and promote rural energy independence. This local-resource approach can strengthen supply chains and user acceptance.

This study aims to investigate the sustainable production and performance characteristics of biomass briquettes made from coffee husks and cow dung, using varying blend ratios. Coffee husks, an abundant agricultural residue in coffee-producing regions, present a promising renewable fuel source but face limitations such as low bulk density and poor combustion efficiency. Cow dung, a widely available organic binder, offers potential to enhance the binding, combustion, and structural properties of briquettes. The specific objectives of this study are to evaluate the physico-mechanical properties (density and compressive strength), thermal and chemical composition (moisture content, volatile matter, ash content, and calorific value), and combustion characteristics (burning rate and specific fuel consumption) of the briquettes. Additionally, the study assesses their emission profiles (NOx and SO_2 concentrations) to determine environmental compatibility. All tests were conducted according to relevant ASTM and ASAE standards to ensure methodological consistency and reliability. Together, these metrics provide a comprehensive basis for performance comparison.

The expected outcomes of this research include identifying the optimal mixing ratio of coffee husks and cow dung that achieves the best performance in terms of energy content, mechanical strength, and environmental safety. The findings will provide valuable insights into the viability of converting agro-waste into efficient and sustainable biofuels, supporting local energy solutions in rural and coffee-growing regions. Moreover, the study contributes to broader discussions on sustainable energy transitions, low-emission biomass utilization, and circular bioeconomy models in developing countries. The results are intended to inform both technical design and policy-focused clean cooking initiatives.

Figure 1 CIR (a) LOS and (b) NLOS.

parametric Probability Density Function (PDF) and Kullback Leibler distance, and a maximum likelihood ratio test. In this paper, we use Skewness, Kurtosis, RDS, MED and Energy for channel clarification. We also introduce new parameters such as Energy Ratio, Mean of Covariance Matrix and Joint probability distribution function.

The remaining part of the paper is organized as follows: Section III details the methodology employed in this research, while Section IV presents the simulation results. Finally, in Section V, we summarize our conclusions and recommendations for future work.

2.0 Materials and Methods

In this section, the materials and methods for this research are presented. Starting from the channel, it can be completely described by its impulse response. In the UWB communication system information is sent via very narrow pulses over the channel. At the receiver end, these pulses can be approximated by the channel impulse response. As can be seen from Fig. 1, the Channel Impulse Response (CIR) is distinct for LOS and NLOS scenarios. This difference in CIR for LOS/NLOS can be exploited for channel state identification. Various parameters calculated from CIR like Skewness, Kurtosis etc. can be utilized to statistically distinguish between LOS/NLOS propagation channel.

2.0 Materials and Methods

2.1. Sample Collection and Preparation

The raw materials used in this study were coffee husks and cow dung. Coffee husks were collected from local coffee processing factories immediately after the milling stage, where they are generated as a by-product during dry milling. Upon collection, the husks were manually sorted to eliminate contaminants such as stones, soil, plant debris, and other foreign matter that could interfere with the combustion and densification properties of the resulting briquettes. The sorted coffee husks were then air-dried to reduce surface moisture content before further processing.

Cow dung, serving as the natural binder, was sourced from a nearby livestock farm. The fresh dung was initially sun-dried to reduce moisture and then subjected to oven drying at 105 °C for 18 hours to achieve a bone-dry condition, thereby minimizing microbial activity and ensuring uniformity in moisture content during blending.

Figure 1: Process flow for producing coffee-husk briquettes with cow-dung binder

Figure 1 illustrates the stepwise procedure adopted to produce briquettes using coffee husks and cow dung. The process involved a series of preparatory and forming stages designed to improve the homogeneity and performance characteristics of the briquettes. In the particle size reduction phase, both coffee husks and dried cow dung were ground using a mechanical mill and sieved using a standard Tyler mesh. The coffee husks were passed through a 1.18 mm mesh, while the cow dung was sieved through a 0.6 mm mesh to achieve uniform particle sizes. This sieving process ensures better compaction, increased surface area for combustion, and improved bonding between particles during briquetting. The two materials were then blended in different weight ratios to study the effect of cow dung binder concentration on the physical, mechanical, and combustion properties of the briquettes. The blending ratios (coffee husks:cow dung) used were 100:0, 90:10, 80:20, and 70:30. Each formulation was thoroughly mixed to ensure homogeneity before the compaction process. For briquette formation, a manually operated compressive testing machine was employed to apply a compressive load of 25 kN. This load was found to be sufficient for achieving high-density compaction without causing cracking or structural failure of the briquettes. The compaction was conducted at ambient room temperature using cylindrical molds of consistent dimensions. The freshly formed briquettes were carefully removed from the mold and subsequently dried in a laboratory oven at a temperature of 105 °C for 18 hours. This drying step was essential to eliminate residual moisture, which could otherwise hinder combustion performance and promote microbial degradation during storage. The dried briquettes were then stored in airtight containers to prevent moisture absorption from the atmosphere prior to further analysis and testing.

2.2. Experimental Methods

This section outlines the experimental procedures used to evaluate the physical, mechanical, and combustion properties of the briquettes produced from coffee husks and cow dung. Standard testing protocols and internationally accepted methods were employed to ensure the reproducibility and accuracy of the results.

2.2.1. Moisture Content

The test samples were carried out at about 105 °C for 2 hrs. And allowed to stay in a room for about 3 days at a room temperature of 25 °C before moisture content test according to ASTM D1762-84.50g of coffee husk briquettes were measured as W_1 and placed in an oven for 2 hours at a temperature of 105 °C for drying [31]. After the samples were removed and their weights measured as W_2, the difference in weights and moisture content (MC) was determined from the eqn. (1).

$$MC = \frac{W_1 - W_2}{W_1} \times 100\% \quad (1)$$

Where, MC = percentage of moisture content, W_1 = Initial weight of the sample before oven drying in g, and W_2 = final weight of the sample after oven drying in g

2.2.2. Density

Density is a critical parameter influencing the energy content, combustion efficiency, and transport economics of biomass briquettes. Denser briquettes are associated with longer burning durations, making them more suitable for household heating and cooking applications [32]. The bulk density of the briquettes was measured according to the American Society of Agricultural Engineers standard ASAE S269.4 (1991). The volume of each briquette (Vp) was calculated assuming a cylindrical shape using the eqn. (2) and the bulk density from eqn. (3).

$$v_p = \frac{\pi}{4} D^2 L \quad (2)$$

$$\rho_b = \frac{Mp}{Vp} \quad (3)$$

Where ρ_b - The bulk density (kg/m^3), Mp- weight of powder (g), Vp - volume of powder, L- length and D – diameter of the briquettes.

2.2.2. Compressive strength

Compressive strength is an essential mechanical property that determines the ability of the briquettes to withstand handling, storage, and transportation without disintegration. The compressive strength was measured using a Universal Testing Machine (INSTRON 3382) equipped with a 50 kN load cell, as per ASTM D2166-85 standard [33]. The crosshead speed was maintained at 1 mm/min, and the peak load at failure was recorded. Each briquette sample was tested in triplicate, and average values were reported.

2.2.3. Proximate Analysis

Proximate analysis was conducted to determine the volatile matter, ash content, and fixed carbon, which are indicative of the fuel quality and combustion behavior of the briquettes.

2.2.3.1. Volatile Matter

Volatile matter was determined using ASTM D3175-11 procedure. Five grams of oven-dried briquette samples were placed in a covered platinum crucible and heated at 900°C for 7 minutes in a muffle furnace. After heating, the crucibles were cooled in a desiccator and reweighed [34].

The loss in weight were recorded as the percentage volatile matter of the produced briquettes. The percentage of volatile matter was calculated using Eqn. (4).

$$\%VM = \frac{M-N}{M} \times 100\% \quad (4)$$

%VM = Percentage volatile matter, M= Initial mass of the briquette sample before burning in a blast furnace, N = Final mass of the briquette sample after burning in a muffle furnace.

2.2.3.2. Ash Content

Ash content reflects the non-combustible mineral residue remaining after complete combustion of the fuel. Ten grams of each briquette sample were placed in open crucibles and combusted in a muffle furnace at 575°C for 3 hours [31]. The crucibles were then cooled in a desiccator and weighed. Ash content was computed using Eqn. (5):

$$\%\text{Ash content} = \frac{M_f}{M_i} \times 100\% \quad (5)$$

Where M_f is the weight of ash and M_i. is the original weight of sample.

2.2.3.3. Fixed Carbon

Fixed carbon is the solid combustible residue that remains after the volatile matter is driven off. It was calculated by subtracting the sum of ash, volatile matter, and moisture content (determined separately) from 100%, as shown in Eqn. (6) [35].

$$\text{Fixed carbon} = 100\% - (\text{Ash}\% + \text{volatile }\% + \text{moisture }\%) \quad (6)$$

2.2.4. Burning rates

Burning rate indicates the rate of mass loss during combustion, providing insight into how quickly the fuel burns. Approximately 120 g of each briquette sample was ignited in a traditional charcoal stove. Mass reduction was recorded at 15-minute intervals using a digital balance until a near-constant mass was observed, indicating complete combustion [36]. Burning rate was calculated using Eqn. (7):

$$\text{Burning rate (q)} = \frac{m}{t} \quad (7)$$

2.2.5. Thermal Gravimetric Analysis (TGA)

A thermogravimetric analyzer (TGA) (Haan, Germany) was used to investigate the thermal properties of the briquettes. The TGA experiments were conducted at a room temperature of approximately 25 °C. The primary objective of the TGA analysis was to evaluate the weight loss of the briquettes as a function of temperature variation [37]. This technique facilitated the determination of peak combustion temperatures and provided insights into the reactivity of the briquettes under high-temperature conditions. Moreover, the TGA analysis yielded combustion characteristics through differential thermogravimetric (DTG) curves.

2.2.6. Water Boiling Test (WBT)

The Water Boiling Test (WBT) was used to assess the thermal efficiency and practical performance of the briquettes under controlled cooking conditions. The test was conducted at room temperature (~25°C) using a traditional charcoal stove and a stainless-steel pot with a lid. Each briquette sample was used to heat one liter (1 L) of water, and the time taken to reach boiling point was recorded. This test is essential for evaluating the suitability of briquettes for domestic cooking applications and for comparing specific fuel consumption rates [38].

2.2.6.1. Specific fuel Consumption

Specific Fuel Consumption (SFC) measures the quantity of briquettes required to boil a fixed amount of water. Lower SFC values indicate higher thermal efficiency and better energy performance. It was computed using eqn. (8).

$$\text{Specific fuel Consumption} = \frac{BMass\ of\ briquettes\ consumed\ (g)}{1\ Litre\ of\ water} \quad (8)$$

All tests were conducted in triplicates, and mean values were reported. The procedures ensure consistency and facilitate reliable comparison with existing literature on biomass briquette performance.

3. Results and Discussions

3.1. Physio-mechanical properties

3.1.1. Moisture Content

Moisture content plays a crucial role in determining the quality and combustion performance of biomass briquettes. It directly affects the ignition time, burning efficiency, and storage stability of the briquettes. In the present study, the moisture content of coffee husk briquettes bound with cow dung was measured across different mix ratios.

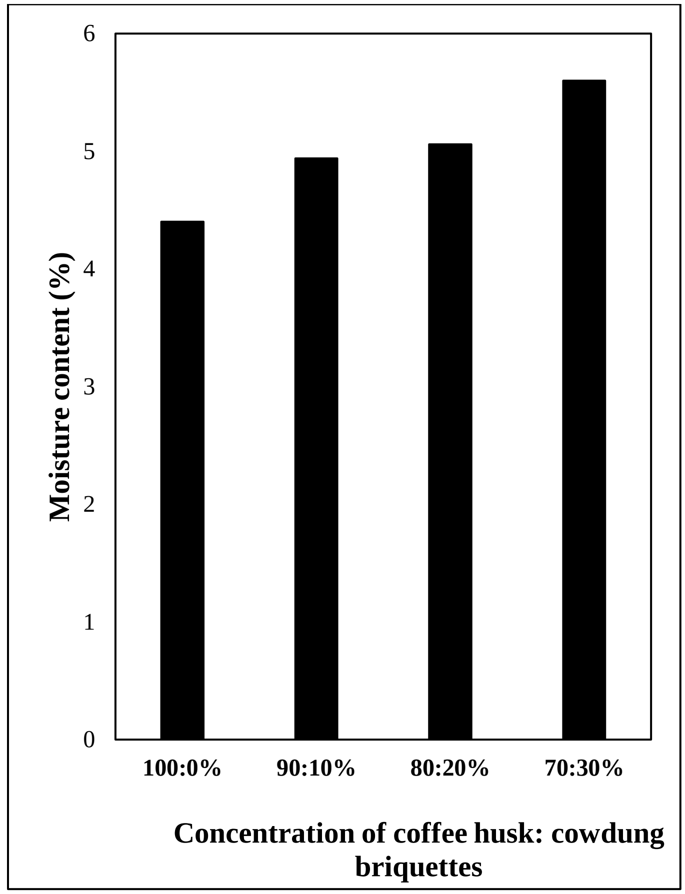

Figure 2: Effect of varying the Concentration of cow dung in the coffee husk/cow dung briquettes on moisture content.

The results shown in Figure 2 indicate that the moisture content of the briquettes increased with the concentration of the binder. The maximum moisture content was observed at a 30% cow dung concentration, while the minimum was found at 0% cow dung concentration, with values of 5.6% and 4.4%, respectively. These results are consistent with the [39] recommendation that the moisture content of high-quality briquettes should be less than 15%. A lower moisture content, as observed in this study, facilitates better heat transfer [40,41]. All briquettes produced in this study meet the specifications for efficient heat transfer, with moisture content not exceeding 10%. As a result, the briquettes are more likely to ignite easily and generate higher calorific values, which is essential for producing high-quality briquettes.

3.1.2. Density

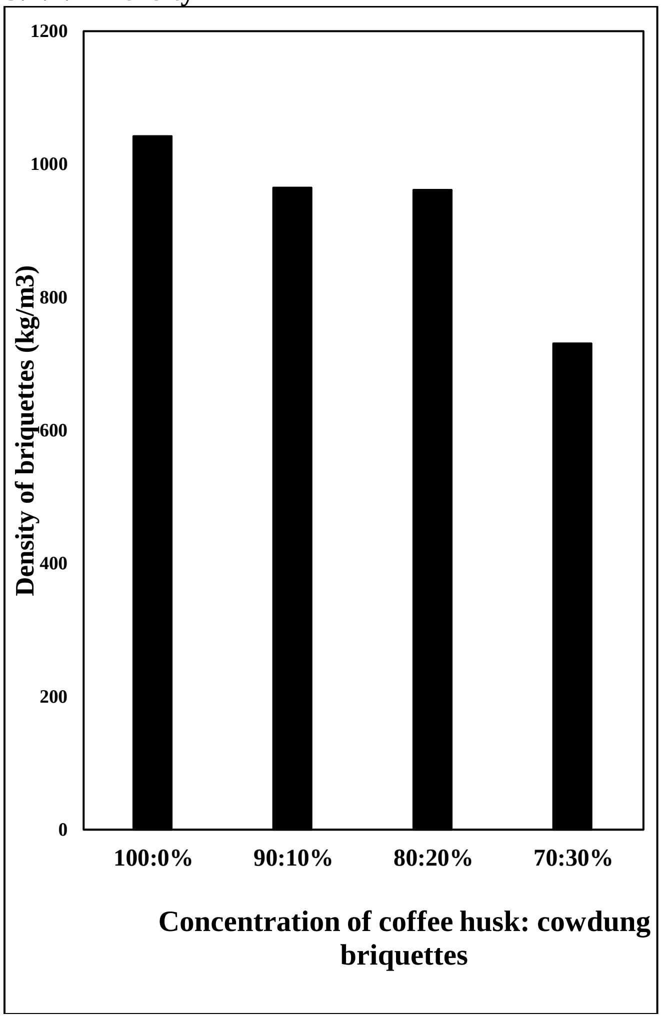

Figure 3: Effect of varying concentrations of cow dung in coffee husk/cow dung briquettes on density

The results shown in Figure 3 indicate that the density of the briquettes produced from coffee husks with 0% cow dung was 1042 kg/m^3, which falls within the recommended range of 900–1300 kg/m^3 for briquettes as specified by the [39]. Briquettes with 10% and 20% cow dung also exhibited densities within the recommended range for quality briquettes. However, briquettes with 30% cow dung concentration had a density of 730.7 kg/m^3, which is below the recommended standard.

3.1.3. Compressive strength

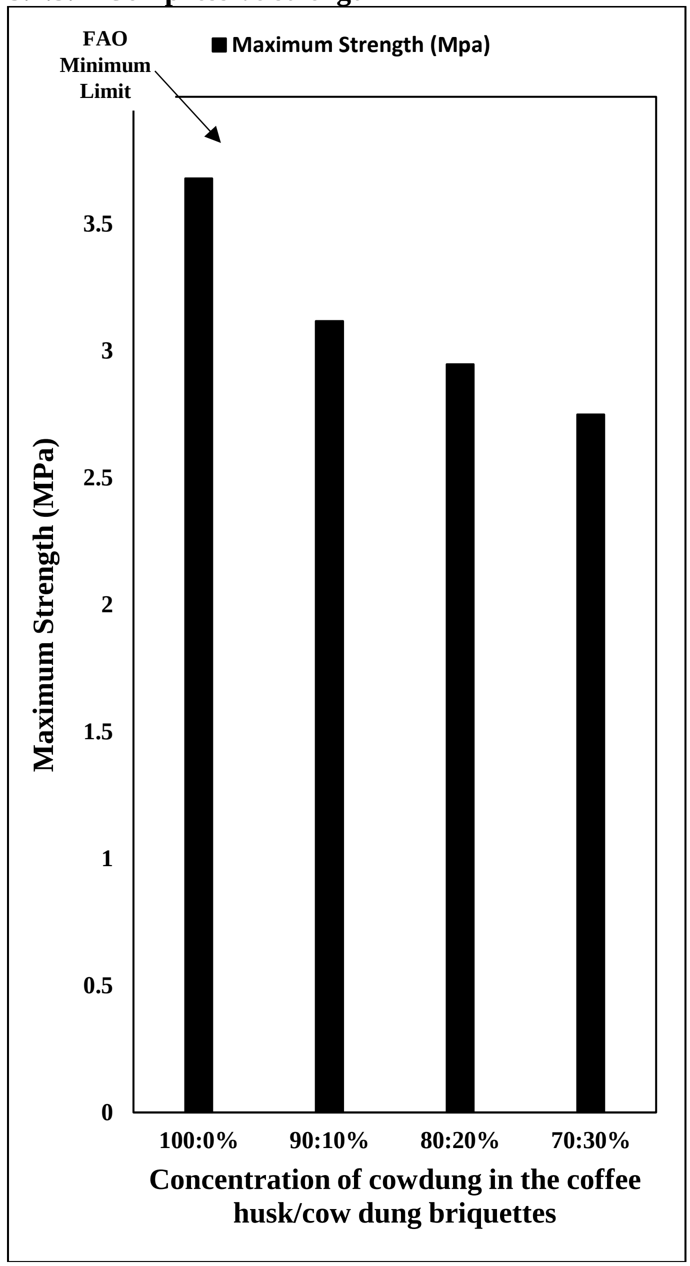

Figure 4: Effect of varying cow dung binder concentrations in coffee husk/cow dung briquettes on compressive strength

The results obtained from Figure 4 show that the compressive strength of the briquettes ranged from a minimum of 2.749 MPa to a maximum of 3.679 MPa for briquettes with 0% to 30% cow dung concentration. The applied load ranged from 5.614 kN to 7.696 kN for the same binder concentrations. The reduction in both compressive strength and applied load indicates that briquettes with higher binder concentrations are less durable, as they are more prone to disintegration when subjected to lower applied loads. Conversely, other research suggests that certain binder types and concentrations can enhance briquette durability and density [42]. The higher compressive strength observed in the coffee husk briquettes with 0% cow dung concentration can be attributed to the homogeneity of the molecular particles in the briquettes. This homogeneity contributes to the stability of the microstructure, which in turn enhances the briquettes' ability to withstand packaging and transport under varying road conditions with minimal spoilage.

3.1.4. Proximate analysis

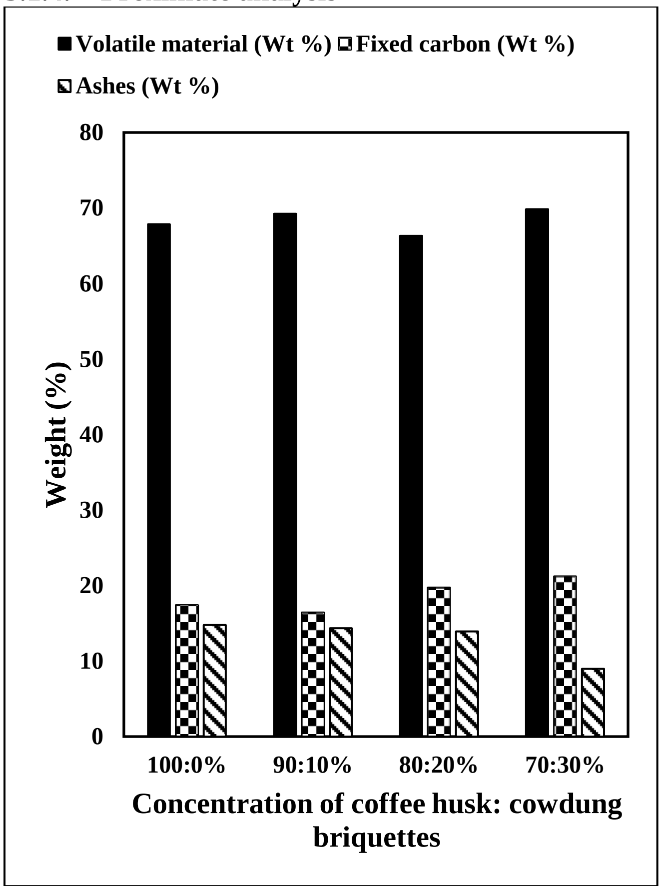

Figure 5: Physical properties of coffee husk/cow dung briquettes with different cow dung concentrations

The physical properties of the developed briquettes are shown in Figure 5. The volatile material content of the produced briquettes ranged from 67.83% to 69.84% in coffee husk briquettes with 0% to 30% cow dung concentration. The trend indicated that an increase in the concentration of cow dung binder led to a slight increase in the volatile material content in each sample. Higher volatile matter content enhances the ignitability of fuel briquettes due to increased chemical reactivity (Sana et al., 2020) and (Del Rio *et al*., 2020).

The fixed carbon content of the produced briquettes ranged from 17.41% to 21.2% in coffee husk briquettes with 0% to 30% cow dung concentration. The trend showed that the concentration of cow dung binder in the briquettes also led to an increase in the fixed carbon content in each sample. Fixed carbon is positively related to the high heating values of briquettes. The results obtained showed lower fixed carbon content compared to rice husks (38.3%), bagasse (49.4%), and groundnut shells (49.5%) [38].

The ash content of the produced briquettes ranged from 8.96% to 14.76% in coffee husk briquettes with 30% to 0% cow dung concentration. The trend indicated that an increase in the concentration of cow dung binder led to a reduction in ash content in each sample. The ash content of the developed briquettes with 30% cow dung concentration was 8.96%, which is lower compared to the 11.9% ash content obtained from rice husks. For cow dung ratios of 10%, 20%, and 30% in coffee husk briquettes, the results were in line with those obtained from groundnut shells and lower than the 39.6% ash content from bagasse briquettes [38].

The reduction in ash content as the concentration of cow dung increased can be attributed to the reduced presence of cellulose and hemicellulose in the briquettes. Ash content significantly influences the heat transfer process in fuel briquettes and the diffusion of air during combustion. Therefore, briquettes made with higher concentrations of cow dung in this study are preferred for higher heating values since they have lower ash content, which enhances their calorific values.

3.1.5. Ultimate analysis

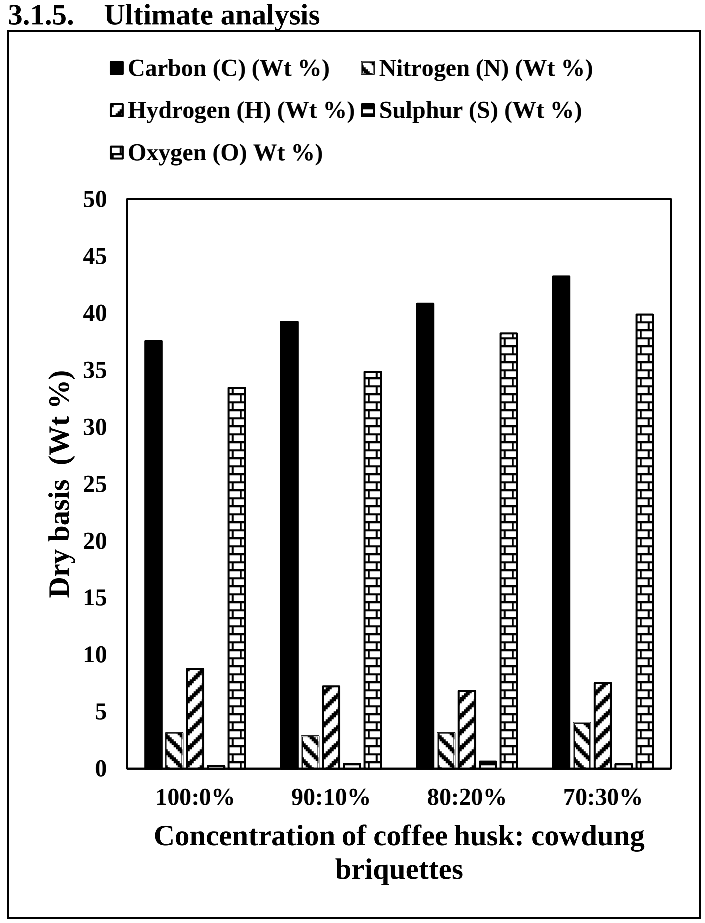

Figure 6: Components of the coffee husk/cow dung briquettes with varying cow dung binder concentrations on dry basis

In Figure 6. In coffee husk briquettes with a cow dung binder, the ultimate analysis results revealed that carbon (C) was the predominant constituent in the briquettes. The maximum carbon content of 43.21 wt. % was found in briquettes with 30% binder concentration, while the minimum was 37.52 wt. % in briquettes made from pure coffee husks. The maximum carbon value was found to be lower than the 45.20 wt. % obtained from rice husks [42]. Hydrogen (H) content ranged from 7.51 wt. % to 8.74 wt. % for briquettes with 30% to 0% binder concentration, respectively. The quantity of hydrogen and carbon content in the produced briquettes indicates that they can burn intensively, as these elements are responsible for combustion. This suggests that more carbon monoxide (CO) and carbon dioxide (CO_2) may be released during the combustion of the briquettes. Oxygen (O_2) content was also found to be relatively high, as it is essential for complete fuel combustion. The maximum amount of oxygen was observed in the briquettes with 30% cow dung binder concentration, with a value of 39.86 wt.%, while the least amount was found in briquettes with no binder concentration (0% binder), at 33.42 wt.%.

Nitrogen (N) content ranged from 2.85 wt. % to 4.02 wt. % for briquettes with 10% to 30% cow dung concentrations, respectively. The nitrogen content increased with the concentration of cow dung, apart from the pure coffee husk briquettes, which had a nitrogen content of 3.12 wt.%. Sulfur (S) content ranged from 0.23 wt. % to 0.61 wt. % for briquettes with 0% to 20% cow dung concentrations. Sulfur content increased with the concentration of cow dung, apart from the briquettes with 30% cow dung concentration, which had a sulfur content of 0.39 wt.%. Both nitrogen and sulfur contents were found to increase as the concentration of cow dung increased in each sample. The study results indicated that nitrogen and sulfur were the least present in the briquettes compared to carbon, hydrogen, and oxygen. Therefore, the briquettes produced in this study are preferred for their lower emissions of nitrogen and sulfur oxides, which are harmful to the atmosphere. As such, the produced briquettes are ideal for environmental sustainability and pose less harm to human health.

3.2. Thermal properties and Emission characterization

3.2.1. Calorific Value

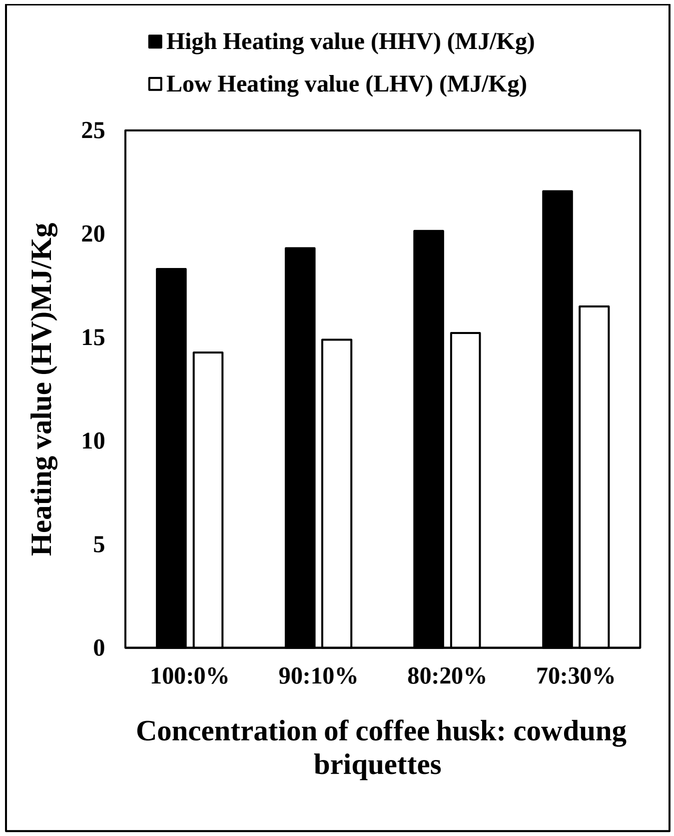

Figure 7: Effect of varying the Concentration of cow dung in the coffee husk/cow dung briquettes on calorific value.

Figure 7 shows the calorific value of the fuel pellet briquettes, as measured using an AVL Digi gas analyzer. The results revealed that the minimum Higher Heating Value (HHV) was found in pure coffee husk briquettes without a cow dung binder, with a value of 18.31 MJ/kg. The highest HHV was obtained from briquettes with a 30% binder concentration with 22.06MJ/Kg. The calorific value increased as the concentration of cow dung in the briquette increased, which was attributed to the mixing of coffee husk and cow dung, enhancing the heating value of the briquettes. Similarly, the Lower Heating Value (LHV) of pure coffee husk briquettes without a cow dung binder was found to be the minimum, at 14.36 MJ/kg, while the maximum LHV was obtained from briquettes with 30% binder concentration, with a value of 16.49 MJ/kg. The calorific value increased as the concentration of cow dung in the briquette increased, further supporting the idea that the blending of coffee husk and cow dung enhances the heating value of the briquettes.

The Higher Heating Value (HHV) of the produced briquettes was found to be higher than that of ecological coal, which has an average HHV of approximately 17.088 ± 0.274 MJ/kg [42]. It was observed that coffee husk briquettes have a higher calorific value, making them suitable for energy-saving applications, in comparison to other briquette materials. For instance, beech wood briquettes have a calorific value of 18.38 MJ/kg, while wheat straw has a value of 17.69 MJ/kg [43]. The briquettes produced in this study also exhibited a Lower Heating Value (LHV) of 16.49 MJ/kg, which is higher than that of rice husks and sugar cane when used with ecological coal. The calorific values for rice husks and sugar cane are 14.54 ± 0.55 MJ/kg and 14.23 MJ/kg, respectively, and align with the LHV of coffee husk briquettes with 0% cow dung concentration [29].

The lowest heating value of the briquettes in this study, with a 20% cow dung concentration. The results demonstrated that the addition of a binder increased the calorific value of the briquettes. This enhancement was due to the compositing of coffee husks with cow dung, which has a higher HHV in the briquetting process [42]. Overall, the briquettes produced in this study are suitable for domestic applications as an alternative energy source.

3.2.2. Burning Rates

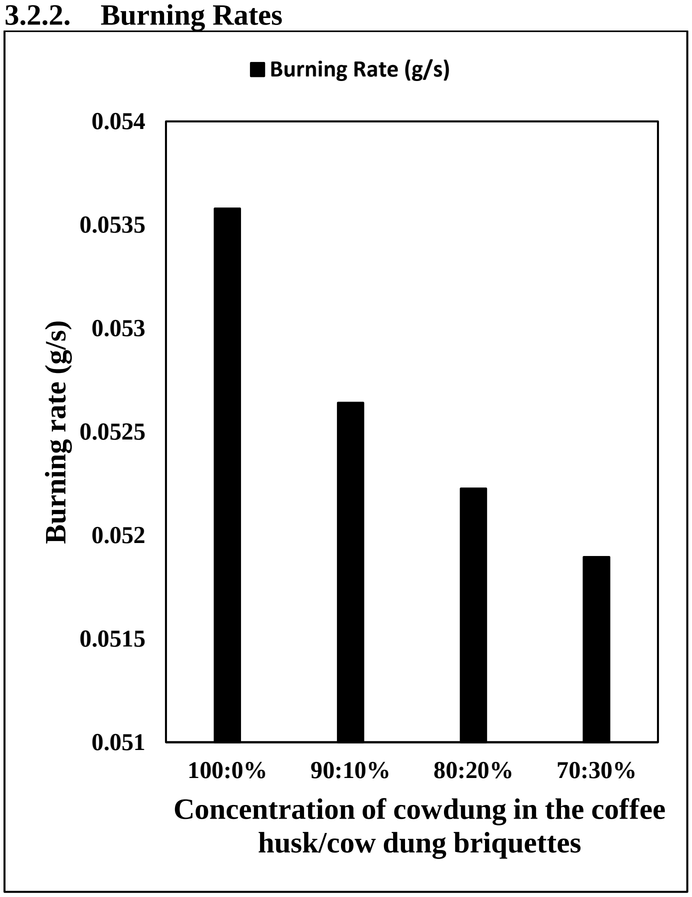

Figure 8: Effect of varying cow dung binder concentrations in coffee husk/cow dung briquettes on Burning rate.

The results in Figure 8 illustrate the relationship between binder concentration and the burning rate of briquettes. As the binder concentration increases, the burning rate decreases. This trend suggests that briquettes with higher binder content burn more slowly, resulting in longer burning durations and improved thermal stability. However, the reduced burning rate may lead to lower energy output, necessitating more fuel for cooking and other applications.

Conversely, briquettes with lower or no binder content ignite more easily and burn more rapidly, producing minimal ash. This characteristic makes them suitable for quick and efficient heating tasks. However, their faster combustion rate implies that a greater quantity of fuel might be required to sustain longer cooking processes.

3.2.3. Thermo gravimetric Analysis of coffee husk briquettes with cow dung binder

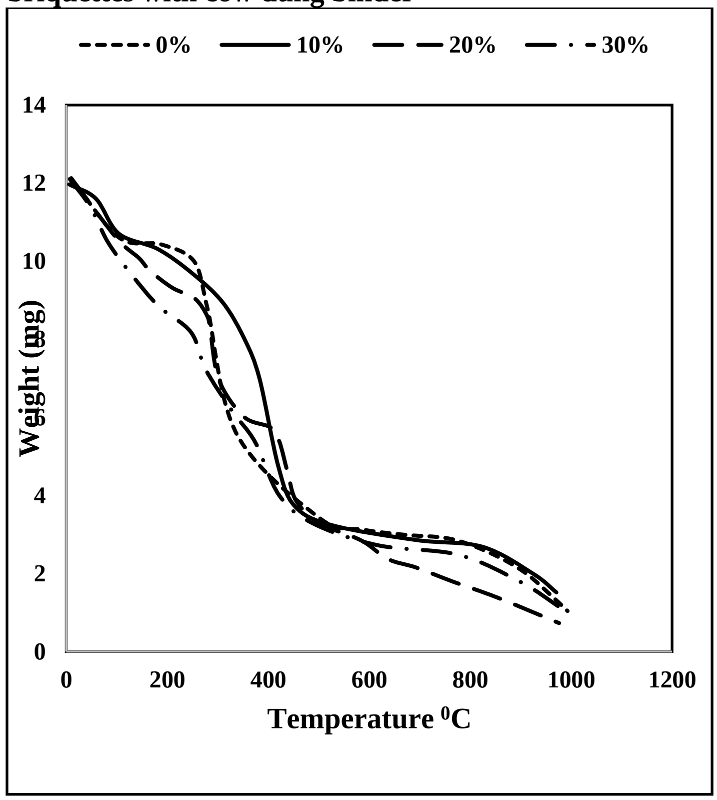

Figure 9: Thermo gravimetric of weight loss for coffee husk: cow dung briquettes with varying concentrations in cow dung binder.

Figure 9 shows the weight loss behavior and thermal stability of coffee husk briquettes with varying concentrations of cow dung binder. The analysis was conducted at 20°C/min according to ASTM E1131 for 41.14 minutes, with temperature increases from room temperature to 1000°C. Figure 9 (0%) shows the weight loss behavior for coffee husk briquettes with 0% cow dung binder concentration. From 0-150°C, a significant weight loss of about 10% occurred due to the evaporation of moisture content. The weight loss continued gradually from 150-300°C, as the volatile compounds and moisture evaporated. Above 300°C, exothermic reactions began, and combustion occurred in regions where hydrocarbons, with low boiling points, were exposed. Weight loss increased drastically from 300-400°C due to the decomposition of hemicellulose, with approximately 40% of the total mass decomposed. The cellulose also broke down, and all other combustible gases were released. From 400°C to 600°C, a gradual weight loss was observed due to lignin decomposition, which occurs at a slower rate and is more thermally stable than cellulose and hemicellulose. Above 600°C, a plateau was reached, indicating the presence of ash content (approximately 10% of the total mass), marking structural stability. However, higher amounts of ash negatively affect energy efficiency. As a result, pure coffee husk burns faster, generating low amounts of ash with high energy but is less stable. Figure 9 (10%) shows the weight loss behavior for coffee husk briquettes with 10% cow dung binder concentration. From 0-150°C, a significant weight loss of about 8% occurred due to the evaporation of moisture. Weight loss continued to increase gradually from 150-300°C due to the evaporation of volatile compounds and moisture. Above 300°C, exothermic reactions began, and combustion occurred in regions where hydrocarbons were highly concentrated. Weight loss increased drastically from 300-400°C due to the decomposition of hemicellulose and cellulose, with all other combustible gases being released. From 400°C to 600°C, gradual weight loss occurred due to lignin decomposition, which is more thermally stable than cellulose and hemicellulose. Above 600°C, a plateau was reached, indicating ash content of about 15%, with structural stability achieved by higher amounts of ash. Although higher ash content can negatively affect energy efficiency, the addition of 10% cow dung binder improved briquette integrity and slowed down combustion.

Figure 9 (20%) shows the weight loss behavior for coffee husk briquettes with 20% cow dung binder concentration. From 0-150°C, a significant weight loss of about 7% occurred due to moisture evaporation. From 150-300°C, weight loss continued gradually due to the evaporation of volatile compounds and moisture. Above 300°C, exothermic reactions started, and combustion occurred in sections with concentrated hydrocarbons. Weight loss increased drastically from 300-400°C due to the decomposition of hemicellulose and cellulose. From 400°C to 600°C, gradual weight loss occurred due to lignin decomposition, which is thermally stable over a broader temperature range. Above 600°C, a plateau was reached, indicating ash content of about 20%, suggesting that the high amounts of ash affect energy efficiency negatively. However, increased ash content confirmed the higher inorganic content from the additional cow dung, which improved structural integrity and extended burn duration but reduced energy output.

Figure 9 (30%) shows the weight loss behavior for coffee husk briquettes with 30% cow dung binder concentration. From 0-150°C, a significant weight loss of about 6% occurred due to moisture evaporation. From 150-300°C, the weight loss increased gradually due to the evaporation of volatile compounds and moisture. Above 300°C, exothermic reactions started, and combustion occurred in areas where hydrocarbons were highly concentrated. Weight loss increased drastically from 300-400°C due to the decomposition of hemicellulose, with approximately 40% of the total mass decomposed. From 400°C to 600°C, gradual weight loss was observed due to lignin decomposition, which is more thermally stable than cellulose and hemicellulose. Above 600°C, a plateau was reached, indicating the highest ash content (about 25% of the total mass), marking structural stability. High ash content negatively affects energy efficiency but increases briquette strength. The higher concentration of cow dung produced longer-burning briquettes, but with lower energy intensity.

The results from Figure 4.8 indicate that higher concentrations of coffee husk material contributed to higher energy output, lower ash content, and faster burning. In contrast, higher concentrations of cow dung increased structural integrity, slowed combustion, and resulted in higher amounts of ash.

3.2.4. Differential Scanning Calorimetry (DSC)

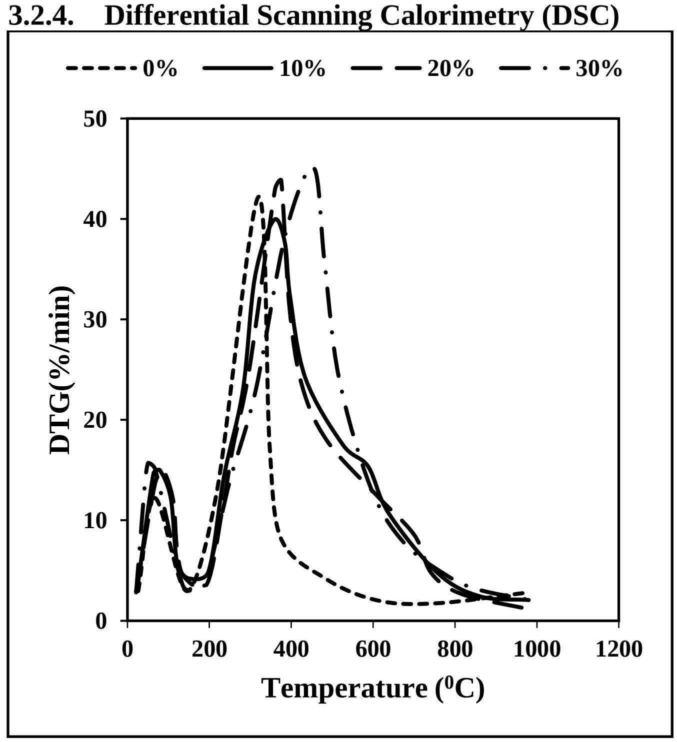

Figure 10: Differential thermo gravimetric (DTG) curves for briquettes with varying cow dung concentrations in coffee husk: cow dung briquettes.

Figure 10 (0%) shows the differential thermo gravimetric (DTG) curves measured using a DSC test at 20°C/min, according to ASTM D 3418, for 40 minutes. The DTG curves displayed two characteristic stages of thermal decomposition for coffee husk briquettes with 0% cow dung binder concentration. The initial stage involved moisture loss at approximately 100°C, caused by the evaporation of residual moisture. The second phase showed the decomposition of hemicellulose and cellulose, occurring at temperatures between 200°C and 400°C. The high-intensity peaks corresponded to the temperatures at which these reactions predominantly occurred, releasing large amounts of volatile matter. Beyond 400°C, a slow and continuous decomposition of lignin occurred, indicating minimal char formation. The curve indicated the fastest ignition, the highest energy release, the shortest burn duration, and the lowest ash residue compared to the later curves.

Figure 10 (10%) shows the DTG curves for coffee husk briquettes with 10% cow dung binder concentration, measured by DSC at 20°C/min, according to ASTM D 3418, for 40 minutes. The DTG curves displayed similar two-phase decomposition. The initial stage involved moisture loss at approximately 100°C, which was slightly lower than the 0% cow dung briquettes due to the presence of cow dung. The second phase showed the decomposition of hemicellulose and cellulose, occurring between 200°C and 400°C, with the peak temperatures indicating the release of volatile gases. The DTG curve exhibited a similar pattern to the 0% cow dung curve but with a slightly lower exothermic peak due to reduced coffee husk content. Beyond 400°C, increased char formation occurred, indicating a higher residual mass. The curve suggested a better balance between ignition speed, burn duration, and improved structural integrity.

Figure 10 (20%) shows the DTG curves for coffee husk briquettes with 20% cow dung binder concentration, measured by DSC at 20°C/min, according to ASTM D 3418, for 40 minutes. The initial stage showed moisture loss at approximately 100°C, like the 10% cow dung curve, due to the evaporation of residual water. The second phase involved the decomposition of hemicellulose, lignin, and cellulose, occurring at temperatures between 250°C and 450°C,with slightly higher residual mass compared to the 10% cow dung briquettes. The peaks represented the release of volatile gases, and after 500°C, more char was produced, with longer combustion duration. The curve indicated moderate ignition speed, improved thermal stability, better burn duration, and higher char formation.

Figure 10 (30%) shows the DTG curves for coffee husk briquettes with 30% cow dung binder concentration, measured by DSC at 20°C/min, according to ASTM D 3418, for 40 minutes. The initial stage showed moisture loss at approximately 100°C, which was slightly higher than in the other curves due to the increased concentration of cow dung binder. The second phase involved the decomposition of hemicellulose and cellulose at temperatures between 250°C and 450°C, with high-intensity peaks corresponding to the predominant reactions. The DTG curve showed the lowest peak, indicating more stable and controlled burning compared to the previous curves. Beyond 500°C, the decomposition occurred, leading to the highest char formation and a longer burning period, accompanied by more ash content.The curve signified the slowest ignition, longest burning time, and highest ash residue, making it suitable for long-term heating applications. The results from Figure 10 show that high concentrations of coffee husk in briquettes result in fast ignition, high volatile release, and minimal ash, making them ideal for quick and efficient combustion, as seen in the briquettes with 100:0 and 90:10 coffee husk to cow dung ratios. As the cow dung content increases (80:20, 70:30 ratios), ignition slows, burn duration increases, and residual char increases, improving thermal stability but reducing energy output. The 90:10 ratio provides the best balance between combustion efficiency and burn duration, while the 70:30 ratio is optimal for prolonged heating applications due to its higher char retention.

3.2.5. Emission analysis

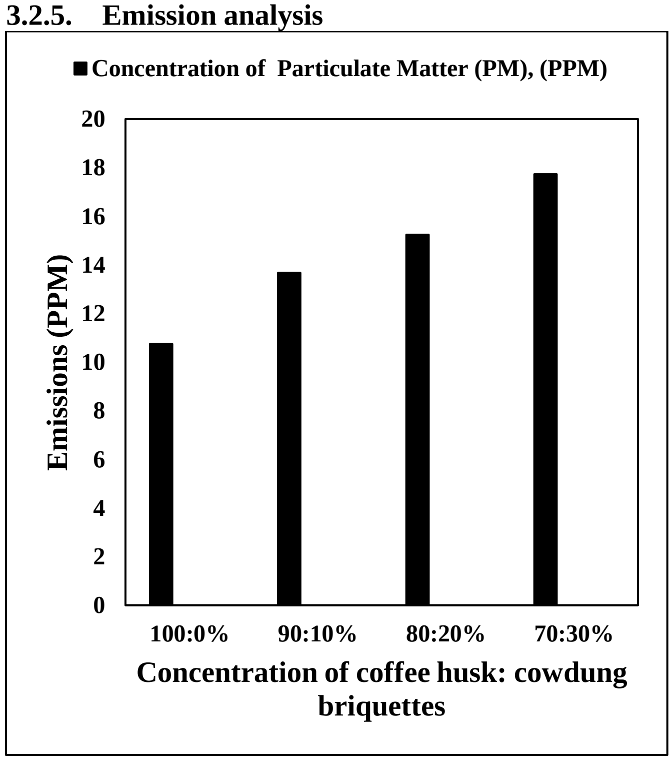

Figure 11: Emitted Particulate Matter from coffee husk/cow dung briquettes with varying cow dung concentrations.

Figure 11 shows the emission components of the developed briquettes measured from 10x6 pellets at a maximum temperature of 625°C using an AVL Digi gas analyzer. The particulate matter (PM) in the produced briquettes ranged from 10.75 to 17.73 Parts per Million (PPM) in coffee husk briquettes with varying cow dung concentrations (0% to 30%). The results showed that as the concentration of cow dung binder increases also the particulate matter increases in the briquettes. This was due to presence of cow dung that releases high amounts of volatile materials during combustion. The PM levels were also in line with the limits set by the FAO of not exceeding 30.68 PPM and the OSHA standards of 25 PPM [39,44]. Therefore, the produced briquettes will not have any negative impact on the environment.

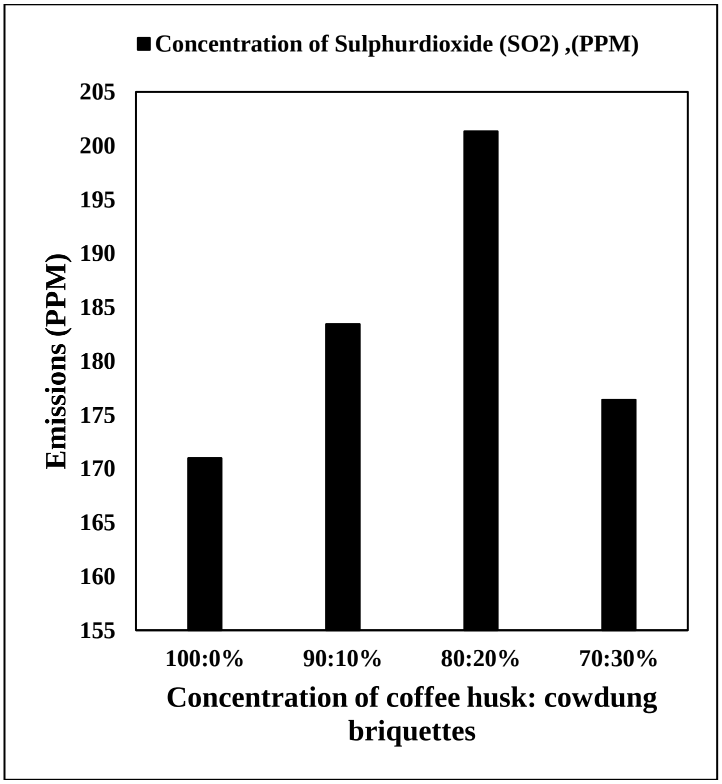

Figure 12: Emitted Sulphur dioxide from coffee husk/ cow dung briquettes with varying cow dung concentrations.

Figure 12 in below shows the emission components of the developed briquettes measured from 10x6 pellets at a maximum temperature of 625°C using an AVL Digi gas analyzer. The sulfur dioxide (SO_2) emissions from the produced briquettes ranged from 170.99 to 201.32 PPM for coffee husk briquettes with 0% to 20% cow dung concentration. This trend showed that, an increase in the concentration of cow dung binder in the briquettes resulted in higher sulfur dioxide emissions, except for the 30% binder concentration, which had a varying value of 176.41 PPM, deviating from the general trend. Elevated SO_2 levels can lead to acid rain formation, which adversely affects soil quality, aquatic ecosystems, and vegetation. However, the SO_2 emissions from the briquettes remain within the range of lower Sulphur coals of (50 - 200) PPM [45–47], thus rendering produced briquettes ideal for application with no harm to the environment.

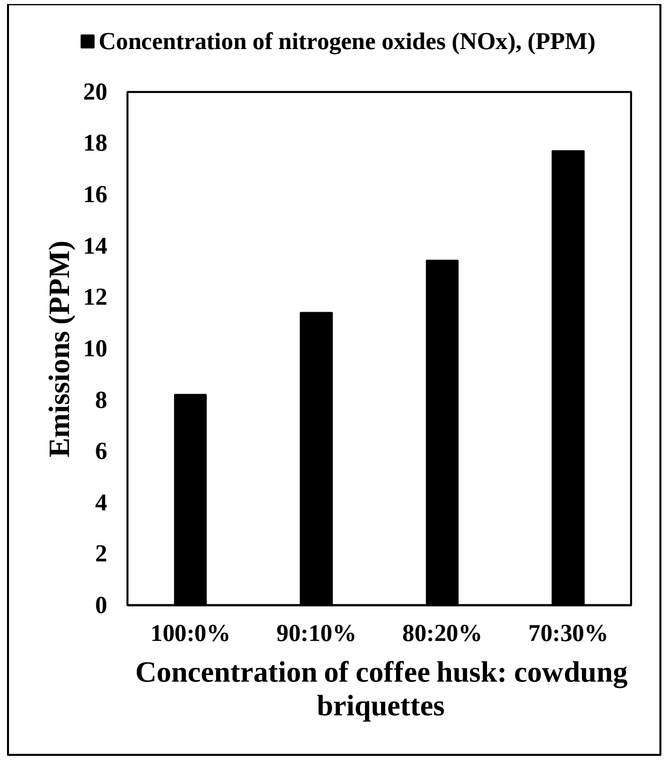

Figure 13: Emitted Nitrogen Oxides from coffee husk/cow dung briquettes with varying cow dung concentrations.

Figure 13 shows the Nitrogen Oxides of the developed briquettes measured from 10x6 pellets at a maximum temperature of 625°C using an AVL Digi gas analyzer. The trend indicated that an increase in the concentration of cow dung binder also led to an increase in nitrogen oxide emissions. The emission values for NOx from the 20% cow dung concentration were like those obtained by [48], when cow dung binder was used with groundnut shells. NOx emissions contribute to air pollution, leading to respiratory issues and the formation of ground-level ozone. However, the NOx levels in the all briquettes are lower than those from certain biomass sources, such as yellow thatching grass (20.1 PPM), groundnut stems and leaves (26 PPM), and a combined recipe (30 PPM) as reported by [48].

The nitrogen (N) component in the fuel contributed to the formation of N2, NO_2, and NOx. The NOx emissions occurred due to the reaction of nitrogen in the air at temperatures above 1300°C. Importantly, the NOx emissions from all the produced briquettes did not exceed the set standards [45–47].

3.2.6. Water Boiling Test (WBT)

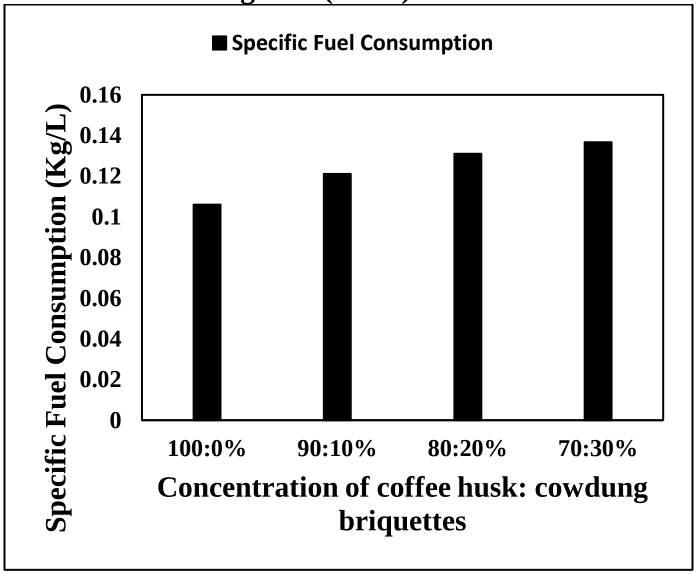

Figure 14: Effect of varying cow dung binder concentrations in the coffee husk/cow dung briquettes on Specific fuel Consumption

The water boiling test results from Figure 14 Showed that pure coffee husk briquettes took shorter time 27 minutes of to boil one (1) liter (L) of water while consuming the least mass of 143.95grams, followed by 10% cow dung concentration with 128.91grams consumed in 29 minutes, 20% cow dung concentration with 130.95grams consumed in 33 minutes and 30% cow dung concentration with 136.65grams consumed in 33 minutes. The trend showed that the increase in binder concentration led to an increase in both mass and time requirement. Pure coffee husk briquettes were the fastest in boiling water and consuming less fuel due to quick ignitability due to high volatile matter content, minimal ash that enhances on oxygen circulation that stimulates fast and efficient combustion. Briquettes with 30% cow dung concentrations too long periods to boil 1L water due to slow ignitability that is caused by low levels of volatile matter and high amounts of char that restricted aeration during combustion but they can retain heat for long periods.

Figure 14, shows the effect of varying cow dung binder concentrations in coffee husk briquettes on Specific fuel Consumption. The results showed briquettes made from pure coffee husk briquettes were the fastest to combust and boil one liter of water in less time compared to the rest and consuming the least time amongst with 0.10605Kg/L. Briquettes with 30% cow dung concentration was found to consume the maximum mass of 136.65g among others and it took too long to boil one liter of water. Therefore, the results obtained signified that pure coffee husks briquettes were ideal for short period cooking activities and coffee husks with 30% cow dung concentrations are ideal for long period cooking applications.

4. Conclusions

The utilization of agricultural waste is highly valuable for energy sustainability, particularly for domestic applications such as cooking and heating, as an alternative fuel source. In this work, the development and characterization of coffee husks/cow dung briquettes were carried out. The developed coffee husk/cow dung briquettes were characterized for physical, mechanical, chemical, thermal, and emission properties at varying blend ratios. The proximate properties analyzed include volatile matter, moisture content, fixed carbon, and ash content. The mechanical properties assessed comprised compressive strength and density. Thermal properties investigated include heating value and thermal degradation weight loss. Chemical analysis involved determining the concentrations of nitrogen, sulfur, carbon, hydrogen, and oxygen. Emission analysis covered nitrogen oxides (NOx), sulfur dioxide (SO2), and particulate matter (PM). The Water Boiling Test (WBT) and specific fuel consumption were also performed, and the following conclusions were drawn;

- The study successfully developed biomass briquettes using different coffee husk to cow dung ratios. The cow dung effectively served as a natural binder, enhancing the structural stability of the briquettes. The 90:10 ratio exhibited a good balance between cohesion, density, and fuel quality.
- Coffee briquettes with (0-20) % cow dung fall with the recommended density limit of between (900-1300) Kg/m^3.
- The compressive strengths of the briquette increase with decrease cow dung constituent with the maximum compressive strength of 3.679MPa at 0% cow dung
- The volatile matter produced briquettes ranges from (67.83 to 69.84) wt. % indicates enhanced briquette ignitability thus increased chemical reactivity.
- The calorific value of 22.06 MJ/Kg from coffee husks with 30% cow dung binder manifested that the briquettes are suitable in generating high energy there by saving fuel during applications.
- Pure coffee husk briquettes with specific fuel consumption of 0.10605Kg/L signified the faster water boiling time, consuming less fuel, quick ignitability due to high volatile matter content and minimal ash that enhances on oxygen circulation that stimulates fast and efficient combustion and ere ideal shorter period applications while Coffee husks briquettes with 30% cow dung concentrations are ideal for long period cooking applications.
- Practically, lower ash content reduces clinker/slag formation and stove fouling (less frequent grate cleaning and better airflow), while higher fixed

carbon extends steady heat output for simmering and long-duration cooking directly improves household stove performance.

- Nitrogen Oxides (NO_X) emission increases as the concentration of cow dung in coffee husk increases. The maximum NOx emission is 17.69PPM. This value is less than the maximum limit of 30.68 PPM and 25PPM set by FAO and OSHA respectively. Thus, the briquettes produced are safe for use.

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Data Availability Statement

All data generated or analyzed during this study are included in this article.

Declarations

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethical Approval: Not applicable.

Consent to Participate: Not applicable.

Consent to Publish: All authors have read and approved the final manuscript and consent to its publication.

Clinical Trials: Not Applicable

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P. Sathish Kumar – Supervision, Project Administration, Writing-Review & Editing

Sanusi Yinka Sofihullahi - Supervision

Milon Selvam Dennison - Original Draft Preparation, Writing-Review & Editing.

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