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Characterization and Combustion Analysis of Densified Fuel Briquettes Made from Bio-Waste Materials †

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Abstract

In this study, fallen leaves of Azadirachta indica and Prunus dulcis were treated as waste materials for the production of energy-intensive bio-coal briquettes. The physical composition revealed that the moisture content ranged from 6.8% to 8.8%, fixed carbon from 10.7% to 14.0%, volatile matter from 71.2% to 77.1%, and ash content from 4.1% to 7.6%. The chemical structure of the biomass fuel, which included carbon, hydrogen, nitrogen, sulfur, and oxygen, was noted to be 44.56–50.69%, 7.12–7.33%, 0.14–0.25%, 0.47–0.79%, and 41.08–47.46%, respectively. The higher heating value ranged from 16.8 to 18.3 MJ/kg. With increasing pressure from 5 to 20 MPa, briquette density increased from 654 to 995 kg/m^3, shatter index from 81% to 94%, durability from 67% to 92%, and resistance to water penetration from 57% to 77%. A low-pressure briquette (5 MPa) burned at a higher rate of 8.0 g/min, whereas a high-pressure briquette (20 MPa) burned at a lower rate of 2.5 g/min. All leaf types tested were able to boil 1000 mL of water with 100 g of briquettes in just 7 min.

Keywords: fallen leaves briquette; proximate analysis; ultimate analysis; water boiling test

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1. Introduction

One of the most important things that humanity needs is energy [1]. The production and use of energy are essential measures of a country's economic success [2]. The majority of the population, roughly 70%, resides in rural areas and uses solid biomass as their primary source of cooking fuel. Bioenergy feedstock consists of agricultural and forestry residues in rural areas, cassava residue, switchgrass, cotton spikes, banana leaves, sawdust,

sawdust, etc. [3,4]. End users in rural areas mainly rely on loose biomass, which is readily accessible and sufficient for boiling water and cooking. Carbon dioxide (CO_2) emissions are reduced when bioenergy is used [5–7].

Researchers have conducted several investigations on the briquetting, physical, chemical, and combustion characteristics of briquettes made from different feedstocks [8]. A study examined the properties of biomass briquettes created with various die pressures between 5 and 7 MPa [9]. The results showed that as the applied pressure increased, the briquette quality enhanced, and the burning rate decreased [10]. Since holding time had little impact on briquette density, the significant factors identified were pressure, temperature, and particle size. It was confirmed that oakwood sawdust for hardwoods produced the most durable briquettes. Three distinct input parameters: moisture content, applied pressure, and temperature were considered for the densification of soda weed without a binder [11]. Statistical analysis software was used to determine the ideal conditions for creating soda weed briquettes. The results demonstrated that a moisture content of around 10%, an applied pressure of 31.4 MPa, and a temperature range of 85 to 105 °C were optimal for creating various briquette shapes. The performance of briquettes made by combining various parameters, such as ratios of corn residues and palm oil tree peel, with 10% by weight of wastepaper as a binder was analyzed [9]. They found that high-quality briquettes could be produced at pressures between 110 and 130 MPa. The results showed that the boiling duration, fuel combustion rate, and specific fuel consumption (SFC) of the 50:50 and 25:75 mixed briquettes were comparable. The 50:50 blend briquette exhibited the highest thermal fuel efficiency among the different blends.

In a study of the mechanical and thermal characteristics of bagasse briquettes with two different particle sizes and three different biodegradable binders (percent weight-to-weight), it was observed that lignocellulosic and cellulosic binders outperformed lignin binders in terms of mechanical and thermal properties. The production rate, physical and chemical properties, and combustion characteristics of briquettes produced under varying working conditions were investigated [12]. They discovered that a mixture of 65% cashew nutshell, 25% areca nutshell, and 10% cassava starch binder by weight produced briquettes at a high production rate. A piston press machine was used to study the manufacture and characteristics of briquettes made from mixed market waste under various operational parameters. The results showed that mixing two distinct residues produced a high-quality briquette [13].

Dried leaves falling from trees may seem typical, but they can be used as biomass source. Sweeping and burning them is an easy way to dispose of them, but doing this repeatedly every day can be a serious issue related to environmental pollution. To make them more useful, the dried fallen leaves of two perennial trees, Almond and Neem, can serve as valuable raw materials for producing composite briquettes. This offers a sustainable and eco-friendly energy source, which can provide a viable solution to this waste problem and offer communities an eco-friendly means of profit. The fallen leaves of Prunus dulcis (Almond) and Azadirachta indica (Neem) were considered for briquette production in this study. The physical, chemical, and combustion characteristics of the Prunus dulcis and Azadirachta indica leaf briquettes were analyzed to assess their feasibility as a bioenergy source for rural households. This research aims to highlight the potential uses of these leaves while producing bio-coal briquettes from otherwise unused leaf waste. Additionally, it helps reduce the amount of waste. Since fallen leaves are often considered waste and only burned, this study also aims to inspire others to make their own briquettes from the leaves collected in their backyards. The sole focus of this work was to use Prunus dulcis and Azadirachta indica leaves to make bio-coal briquettes. In this study, the impact of biomass composition on the ability to produce high-quality briquettes was evaluated, considering factors such as ignition time, water boiling time, and burning time. The heating value and durability performance of the dried leaves were tested to confirm their suitability for briquette production. This research provides a method for reducing dry leaf waste, which could be used as biomass fuel.

2. Materials and Methods

Perennial shrub trees like Prunusdulcis and Azadirachta indica are grown widely in India. The tree leaves that have fallen within the campus were collected for this research work. The densification procedure involved a hydraulic manual piston press.

2.1. Briquette Production

Both fresh and dried leaves were included in the leaf collection. To get rid of any moisture, chopped fallen leaves were sun-dried for 5–7 days, depending on local weather conditions, until a near-constant weight was observed. A cutter is used to reduce dried leaves to small shreds. Shredded leaves are screened using a 2 mm sieve. For two weeks, cut leaves that have been screened are left to dry. The shredded leaves are then manually inserted into a manual hydraulic piston press with a 35 mm internal diameter. The binder utilized was starch. The precise quantity of the combination for each treatment was determined using a weighing scale. The loose biomass was compressed at various pressures between 0 and 20 MPa with a dwell time of 5 s to create briquettes. The compressed pressure was noted by the pressure gauge. A vernier caliper is used to measure the manufactured briquette's height and diameter. The timing of each treatment's ignition, water boiling, and burning was recorded using a stopwatch.

2.2. Briquette Properties

The briquette mixture with various concentrations, as shown in Table 1, was made by combining the binder and biomass of pulverized dried leaves.

Table 1. Concentrations of the treatments.

Treatment	Dry Leaves Powder %	Starch Powder %
1	100	0
2	90	10
3	80	20
4	70	30
5	60	40
6	50	50

The six binder treatment ratios (100:0, 90:10, 80:20, 70:30, 60:40 and 50:50 w/w leaf powder to starch) were selected based on prior literature and preliminary experiments. These ratios were found to offer practical variation in mechanical and combustion performance, and intermediate gradations were included to systematically observe the effect of increasing starch content on briquette properties. The photograph of the prepared composite biomass briquette is shown in Figure 1.

Each briquette was ignited using an external heat source. A timer was used to record the time required for ignition, water to reach boiling point, and complete combustion of the briquette. Ignition was initiated with a Bunsen burner flame, applied uniformly to each sample. To standardize the initial ignition process, the flame was kept in contact with the briquette for a fixed duration of 30 s, ensuring consistent combustion initiation across all tests.

Figure 1. Prepared composite biomass briquette.

In this experiment, the updraft-forced biomass stove was utilized. To combine the fuel and air, forced vortex airflow circulation was used. The cookstove fuel chamber is cylindrical in shape, measuring 15 cm in height and 7.5 cm in diameter. For this cookstove, four distinct flow rate options are available. In this investigation, a single airflow rate of 1.50 L/s was taken into consideration. To ensure uniform airflow conditions across all combustion trials, the airflow was measured and validated prior to testing using an anemometer with an accuracy of ±5%. A fixed voltage power supply was maintained during all experiments to minimize airflow variability, thereby ensuring consistent combustion conditions. An AC charge that could be powered by the blower. The experiment's pot, which is 22 cm in diameter and made of aluminum steel, weighs 250 g while the stove itself weighs 2500 g.

The proximate and ultimate analyses that illustrate the properties of fallen leaf briquettes are shown in Tables 2 and 3. Briquettes were made stronger and more resistant by adding a starch mixture, which also enhanced the amount of volatile matter (VM), moisture content (MC), hydrogen (H), oxygen (O), and carbon (C) in the briquettes. Additionally, it made combustion easier, but it also tends to raise the amount of ash and decrease the calorific value. The trials were made to ascertain how long a supply of bio-coal briquettes will burn. At each test, 100 g of briquettes with their full fuel capacity were loaded into the stove. Physical properties of 90:10 composite briquette are shown in Table 4.

Table 2. Proximate analysis of composite briquettes with various compositions.

Composite Dry Fallen Leaves Powder to Starch Binder Ratio	Proximate Analysis (wt.%, Dry Basis)				
	Moisture M	Fixed Carbon FC	Volatile Matter VM	Ash Content ASH	Gross Calorific Value HHV (MJ/kg)
100:0	8.8	14.0	72.8	4.4	17.43
90:10	7.2	12.3	76.2	4.3	18.30
80:20	6.8	12.8	72.8	7.6	17.50
70:30	8.2	13.8	71.2	6.8	16.80
60:40	7.3	13.3	75.0	4.4	18.11
50:50	8.1	10.7	77.1	4.1	17.06

Table 3. Ultimate analysis of composite briquettes with various compositions.

Composite Dry Fallen Leaves Powder to Starch Binder Ratio	Ultimate Analysis (wt%, Dry Basis)				
	Carbon C	Hydrogen H	Oxygen. O	Sulfur S	Nitrogen N
100:0	44.56	7.16	47.46	0.23	0.59
90:10	49.94	7.33	42.01	0.25	0.47
80:20	50.69	7.3	41.08	0.14	0.79
70:30	48.3	7.12	43.69	0.19	0.7
60:40	49.69	7.3	42.08	0.14	0.79
50:50	46.3	7.12	45.69	0.19	0.7

Table 4. Physical Properties of 90:10 composite briquette.

Pressure (MPa)	**5**	**10**	**15**	**20**
Briquette density (kg/m^3)	654	725	833	995
Shatter Index (%)	81	85	92	94
Durability Index (%)	67	78	84	92
Water penetration resistance (%)	57	63	68	77
Specific fuel consumption (kg/L)	0.125	0.11	0.09	0.07
Burning rate (g/min)	8	6	3.5	2.5

A silica crucible without a lid was used to hold a known quantity (m_1) of briquette samples while being heated to 105 °C. After one hour of oven drying, the crucible was removed from the oven and placed in a desiccator to cool. The dried sample ($m_{2)}$ in the oven was weighed once again. Using Equation (1), the moisture content (MC) was calculated.

$$\text{Moisture content (\%)} = (m_1 - m_2)/m_1 \times 100 \quad (1)$$

A similar crucible with the oven-dried sample (m_2) inside had a vented lid covering it, and it heated for 7 min at 950 ± 20 °C in a muffle furnace. After being removed from the muffle furnace, the crucible was allowed to cool to ambient room temperature and weighed once again (m_3). Using Equation (2), volatile matter (VM) is calculated.

$$\text{Volatile Matter (\%)} = (m_2 - m_3)\ m_1 \times 100 \quad (2)$$

The leftover sample (m_3) resulting from the volatile matter test was placed in a crucible, which was subsequently heated for 30 min at 700 ± 50 °C in a muffle furnace without a lid. It was removed from the muffle furnace, allowed to cool in the desiccator, and then weighed (m_4). Ash content was calculated using Equation (3):

$$\text{Ash Content (\%)} = m_4/m_1 \times 100 \quad (3)$$

Equation (4) was used to determine the sample's fixed carbon content [14]:

$$\text{Fixed Carbon (\%)} = 100 - [\text{MC (\%)} + \text{VM (\%)} + \text{ASH (\%)}] \quad (4)$$

For the elemental composition test, a CHNS analyzer was employed [15]. The oxygen concentration was calculated from the below Equation (5).

$$\text{\% of O} = 100 - (C + H + N + S + ASH) \quad (5)$$

Knowing the compressed briquette's volume allowed researchers to calculate the briquette's density. The volume was determined after the briquette's length and diameter were measured using a vernier caliper. The mass of the briquette is determined using a digital weighing balance. Following was the relationship used to determine density:

$$\text{Briquette density} = \text{mass of the briquette/volume of the compressed briquette, } m_3 \quad (6)$$

The strength of the briquette may be reduced as a result of the transportation and handling of the briquette, which may cause it to break [16]. During this study, a predetermined height of 1 m is allowed for the briquette to fall from. The briquette's average weight was noted, before and after the test. The experiment was run twice. The briquettes' % weight reduction was calculated using

$$\text{Weight loss (\%)} = (\text{Initial briquette weight} - \text{Final briquette weight})/\text{Initial briquette weight} \times 100 \quad (7)$$

$$\text{Shatter resistance (\%)} = 100 - \text{weight loss (\%)} \quad (8)$$

A tumble test can be used to measure durability, one of any briquette's desirable properties. This tumbling duration was selected based on ASTM standard D440-86. Preliminary tests confirmed that this duration was sufficient to assess mechanical robustness. In this experiment, a cubic box measuring 0.3 × 0.3 × 0.45 m was used to confine the briquette, and its initial weight (Wi) before tumbling was noted. On a hollow shaft, the cubical box was mounted diagonally. The cuboid was rotated for 15 min to create the tumbling action. After the briquette tumbled, its final weight (W_f) was recorded. The amount of weight loss as a result of the tumbling action is determined by

$$\text{Weight loss (\%)} = (W_i - W_f)/W_i \times 100 \quad (9)$$

$$\text{Durability index (\%)} = 100 - \text{weight loss (\%)} \quad (10)$$

The water resistance test measures the briquette's ability to resist consuming moisture-containing water while handling and transporting. The briquette's ability to absorb water was assessed by scattering it for 30 s in a jar containing 150 mm of water at ambient temperature. The briquette's abrasion resistance increases with its water resistance. The following relation can be used to determine how much water the briquette has absorbed.

$$\text{Water gained by the briquette (\%)} = (W_f - W_i)/W_i \times 100 \quad (11)$$

$$\text{Water resistance (\%)} = 100 - \text{water gained by the briquette (\%)} \quad (12)$$

where W_i denotes the briquette's initial weight (g) and W_f denotes its final weight (g) following the test (g).

The mass difference between the final batch of briquettes left after each phase and the pre-weighed batch of briquettes is used to calculate the volume of burning bio-coal briquettes required to bring a vessel of water to a boil.

$$\text{Fuel consumed} = \text{Initial weight of briquette} - \text{Final briquette remaining after combustion} \quad (13)$$

To calculate the equivalent dry fuel, the energy required to remove the moisture from the briquettes, which is the quantity of unburned char, must be known. The quantity of dry fuel used is equal to the mass of wet fuel consumed less than the amount of moisture in the bio-coal briquettes.

$$\text{Equivalent dry fuel consumed} = \text{mass of fuel consumed } (1 - \text{moisture condition}) \quad (14)$$

where mass of wet fuel consumed is measured in kg, and moisture fraction is the decimal fraction of moisture content in the briquette (0.08 for 8.0% moisture).

A measurement of the amount of water evaporated during the test is the mass of evaporated water.

$$\text{Water vaporized from the pot} = \text{initial weight of water (W)} - \text{final weight of water after boiling (W)} \quad (15)$$

Specific Fuel Consumption quantifies the mass of fuel required per unit of useful heat output. It is calculated using the formula:

$$\text{SFC} = \text{mass of fuel consumed (kg)/Volume of the water boiled (L)} \quad (16)$$

where mass of fuel consumed is in kilograms (kg) and volume of water boiled is in liters (L). This formula was used during combustion experiments to evaluate briquette efficiency.

The percentage of heat or energy that is utilized is referred to as thermal efficiency. The water boiling test was used to measure this. After measuring the kettle's volume, 2/3 of the water was added. The covered kettle was set atop the biomass stove. In the center of the kettle, a thermometer was mounted. For analysis, 500 g of briquettes were measured and fed. Both the ambient temperature and the water's initial temperature in the kettle were gauged. After boiling, the water's final temperature was measured. After the briquettes had all been used up, the water was heated again, the kettle cover was taken off, and the evaporation process was repeated for another 20 min. The kettle was then removed from the stove and left to cool for two hours, and the amount of water within was measured. The formula described below was used to compute the thermal efficiency. The net heat given to the water is represented in the numerator, while the net heat released by the fuel is represented in the denominator.

$$\text{Thermal Efficiency} = \text{(Sensible heat + latent heat)/(Quantity of fuel used} \times \text{calorific value)} = [W_iC_p\,(T_2 - T_1) + L\,(W_i - W_f)]/(m \times \text{HHV}) \quad (17)$$

where W_i = initial volume of water, kg, m = mass of the fuel used, kg, C_p = specific heat of water, J/kg °C = 0.004182 MJ/kg °C, HHV = Calorific value, MJ/kg, T_2 = final temperature of water, °C, T_1 = initial temperature of water, °C, W_f = final volume of water, kg, L = Latent heat of water = 2.26 MJ/kg (540 kcal/kg)

The rate of consumption of a specific mass of bio-coal briquettes reduced to ashes is known as the burning rate [17]. An insulated wire gauge was used in the experiment, which was conducted using a digital scale for weighing. A Bunsen burner is positioned beneath the wire gauge and is used to light the briquette that was placed on it. A stopwatch was used to record the amount of time needed to burn the briquette to ashes. The weight of the briquette was measured every 10 s until a steady weight was noticed. The burning rate was calculated using the relationship shown below.

$$\text{Burning rate} = \text{Ash weight (kg)/total time taken (min)} \quad (18)$$

Boiling 1000 cc of water with 100 g of fuel in one batch allowed the water boiling test (WBT) method to calculate the stove's efficiency and correlate it to the effectiveness of each bio-coal composite briquette. The WBT was conducted in accordance with ASTM testing procedures, and a stove with a 1000 cm^3 volume was used for the briquette testing. The WBT calculation was performed to govern the importance of stove efficiency, water-boiling time, and firepower.

The water boiling test consisted of three stages: a cold start, a hot start, and a simmering phase. In the cold start experiment, the fuels were burned at ambient room temperature. Temperature readings were taken every minute using a thermocouple placed inside the pan, while both the water and flame temperatures were recorded. The hot start phase followed a similar procedure; however, since the biomass stove retained heat from the cold start experiment, the briquettes were burned at an elevated temperature. The vessel was then carefully placed on top of the biomass cookstove and left for 45 min to evaluate the performance of the bio-coal briquettes, after assessing the boiling time and fluid mass transfer during the hot start phase. Finally, the mass of the water and the boiling temperature were measured, and the data were processed.

3. Results and Discussion

Tables 2 and 3 show that the sulfur and nitrogen concentration in the fuel is less than 1%. Water boiling test setup is shown in Figure 2. It is well known that burning briquettes that have sulfur and nitrogen contents of less than 1% reduces air pollution. The composite of Prunusdulcis and Azadirachta indica briquettes had moisture content values of 6.8% to 8.8%. The following relation was used to determine the amount of specific fuel consumed throughout the experiment.

$$\text{Specific fuel consumption} = \text{mass of fuel consumed}/\text{total mass of boiling water (L)} \quad (19)$$

Table 4 displays the variation in briquette density at pressures between 5 and 20 MPa. Briquette density is seen to rise as pressure is applied more intensely. A 5 MPa applied pressure results in the lowest density of 654 kg/m^3, and a 20 MPa applied pressure results in the highest density of 995 kg/m^3. More leaf particles can fit into a given volume by increasing the bonding between leaf particles as pressure rises and decreasing the porosity structure. Compaction reduces voids, allowing more uniform particle packing within a fixed volume, which contributes to increased briquette density and strength. Due to their relatively porous structure, lower-density briquettes are more likely to develop cracks during handling, storage, and transportation.

The fluctuation of the briquette shattering index with pressure is seen in Table 4. With a pressurized briquette with a pressure of 5 MPa, the lowest value of the shatter index is 81 percent, and for a 20 MPa pressure, the highest value of the shatter index is 94 percent. Because the chopped leaves are only loosely bound at this pressure during the compaction process, briquette weight loss is extreme in 5 MPa pressure briquettes. For simple handling and transportation, the shatter index should be greater than or equal to 95%. From the current study, it can be inferred that briquettes manufactured at pressures exceeding 20 MPa may be a good choice when taking the shatter index into account.

According to Table 4, for a pressure increase from 5 to 20 MPa, the briquette's durability increased from 67 to 92%. According to research, less than 70% of the durability index can cause briquettes to exhale dust [18]. Additionally, a briquette is deemed to be of high quality for handling, storing, and transporting when it has a durability index above 80%. As a result, the study shows that briquettes made at pressures more than 15 MPa are of high quality.

Briquettes of high quality ought to be less prone to absorbing water when being transported and kept for an extended period. According to Table 4, the highest value of 77% water penetration resistance is achieved with an applied compaction pressure of

20 MPa. This increase in compaction pressure is brought on by the reduced water absorption rate caused by the smaller spaces between the ground leaf particles in the bio-coal composite briquette.

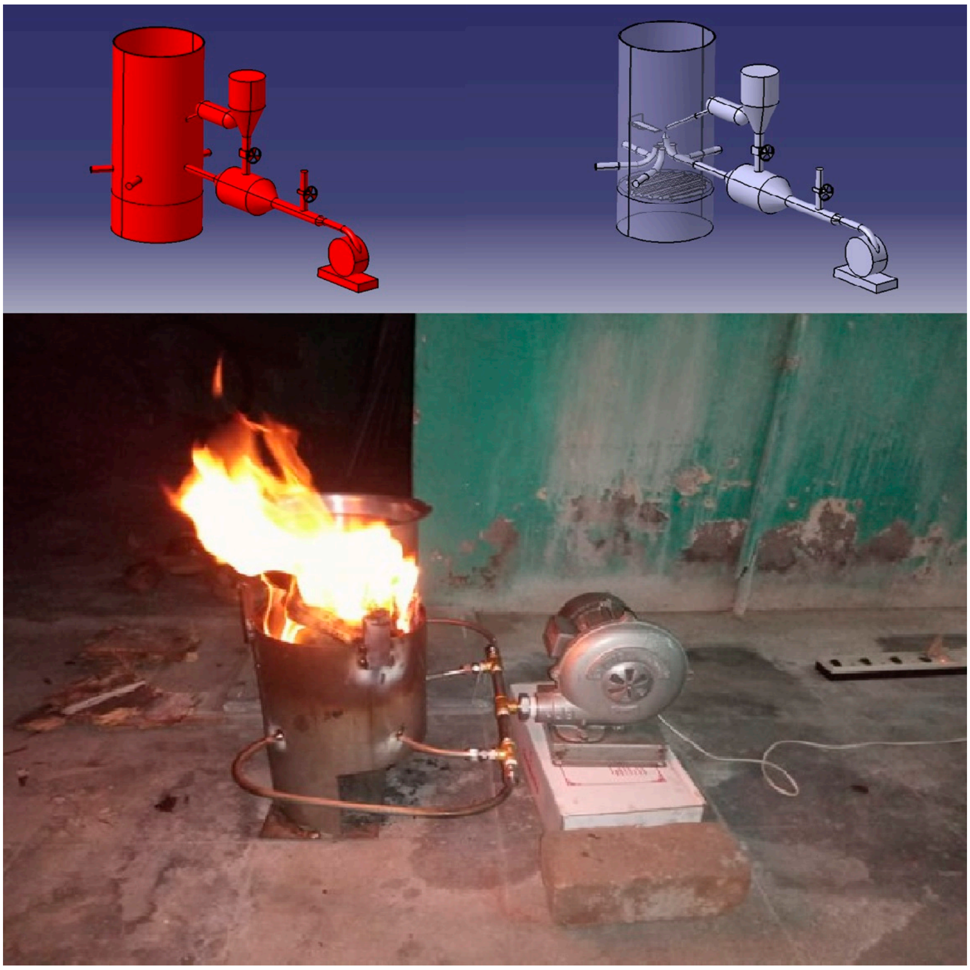

Figure 2. Water boiling test setup.

Table 4 shows that when pressure increases, the burning rate considerably decreases. By reducing voids in the briquette sample, increasing briquette density lowers the rate of mass loss during briquette burning. A low-pressurized briquette at 5 MPa reveals an increased burning rate of 8 g/min. A cylindrical briquette's high packing factor, which restricts air circulation within a briquette during ignition, results in a decreased burning rate of 2.5 g/min for a 20 MPa-pressurized briquette. The density of the briquette rises with pressure, prolonging the time it takes for igniting. As a result, densified briquettes require less SFC [19]. Table 4 shows that a low-pressurized briquette of 5 MPa has a higher SFC of 0.125 kg/L which leads to high fuel consumption as well as more pollution, whereas a high-pressurized briquette of 20 MPa in a manual hydraulic piston press machine has a lower SFC of 0.07 kg/L, which shows a minimum amount of briquette used in the ignition.

4. Conclusions

According to the study, leaves from Prunus dulcis and Azadirachta indica can be utilized to produce briquettes that can serve as cooking fuel in rural regions. At pressures above 20 MPa, the briquettes exhibited favorable physical characteristics, indicating their potential as an effective biomass fuel for rural applications. It was observed that manually densified briquettes were less prone to damage during handling, storage, and transportation. Combustion tests further revealed that high-pressure briquettes demonstrated lower

SFC and reduced burning rates. Moreover, compared to the open burning of unstructured biomass material, briquette combustion contributed less to greenhouse gas emissions due to the higher calorific value and density of densified briquettes. In addition, utilizing loose biomass for briquette production can help prevent deforestation and contribute to the development of a sustainable carbon sink.

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