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Comparative Analysis of Stove Pyrolysis Performance of Donut Briquettes from Bus Wood Waste at Density Variations with and Without Used Oil Injection

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ABSTRACT

This study evaluated the performance of a multilayer pyrolysis stove using donut briquettes from Bus Wood waste (*Melaleuca viridiflora*) at a density of 3, 4, and 5 Mpa, with and without the injection of used oil. The briquettes are arranged vertically in an annular reactor and monitored with nine thermocouples. The test was carried out by measuring the internal temperature distribution and the Water Boiling Test (WBT). The results show a consistent radial temperature gradient; The highest temperature is detected at the inner edges of the briquettes (T3, T6, T9), reaching 650–800 ℃, while the outer edges are below 300–320 ℃. Increasing density from 3, 4, and 5 MPa results in a more stable high temperature and a longer pyrolysis duration. Injection of used oil increases the core temperature, albeit only slightly, at the useful energy of WBT, from 3.7–4.2 to 3.8–4.3 MJ/h. The combination of briquettes with a density of 40–50 bar and injection of used oil is considered the most prospective for the conversion of solid-liquid waste into household heat energy and biochar production in South Papua.

1. INTRODUCTION

The increasing demand for energy around the world is driving efforts to find sustainable and environmentally friendly alternative energy sources [1-3]. In this regard, biomass emerged as one of the top options thanks to its abundant availability, renewable properties, and its potential in reducing dependence on fossil fuels and lowering greenhouse gas emissions [4-9]. One of the most researched methods of thermochemical conversion of biomass is pyrolysis technology, which is known to be capable of producing three energy-valuable products: biochar, bio-oil, and pyrolysis gas [10, 11].

In Indonesia, especially in South Papua, there is great potential in the form of biomass derived from bus wood waste (*Melaleuca viridiflora*), which has not been fully utilized to date [12]. Data on biomass potential inventory and mapping show that the volume of biomass residues from the forestry and agricultural sectors in Indonesia can reach millions of tons per year, with most of it still being wasted in forests or open land [13-15]. The use of bus wood as a raw material for the production of biomass briquettes for pyrolysis stoves is a strategic step in the provision of local renewable energy and contributes to the reduction of lignocellulose waste that has the potential to pollute the environment [16-19].

One of the important elements that affects the performance of biomass briquettes is density, which is affected by the compressive pressure during the production process. High density can increase inter-particle interactions as well as thermal conductivity, thereby contributing to increased combustion stability and slowing down the rate of devolatilization [20, 21]. However, if the density is too high, this can reduce pore permeability and inhibit gas diffusion during the pyrolysis process [22, 23]. Therefore, it is important to explore density variations at the 3, 4, and 5 MPa levels to find the optimal point that can result in maximum energy yield and efficiency.

In addition to the density factor, another approach that can improve the performance of pyrolysis stoves is to add co-fuel. Waste oil, which is liquid waste from automotive activities, has the potential to be used as an additional fuel because it has a high calorific value and suitable characteristics as an alternative fuel [24-26]. Several studies have shown that the addition or co-pyrolysis of used oil in thermochemical systems can improve energy utilization efficiency, accelerate the rate of temperature rise, and increase the yield of liquid/bio-oil fractions [27-29]. However, special studies on the use of used oil injection in pyrolysis stoves using bus wood briquettes are still very limited.

Based on the above explanation, there is an important research space, namely the absence of comparative studies that investigate the performance of pyrolysis stoves with bus wood donut briquettes at different density variations (3–5 MPa), both under conditions with and without waste oil injection. Thus, this study aims to evaluate the thermal performance, pyrolysis characteristics, and the yield level of the resulting product. It is hoped that the results of this study can contribute to the development of local biomass-based renewable energy in Papua and, at the same time, offer innovative solutions in the integrated use of bus wood waste and waste oil to support sustainable energy security [30, 31].

2. THEORETICAL BASIS

The use of biomass as a fuel source for cooking in developing countries remains very common and has a significant impact on pollutant emissions and health problems due to kitchen fumes. The development of better biomass cooking furnaces is rooted in the principle of improving thermal efficiency through airflow regulation, combustion chamber design, and separation between pyrolysis and combustion zones. This aims to make energy release more controlled and particle emissions reduced. Recent research shows that furnaces using gasification and pyrolysis technologies (such as TLUD and downdraft types) can improve efficiency by up to two to three times compared to traditional furnaces, as well as significantly reduce carbon monoxide (CO) and PM_2 emissions, when their design and operation are optimized [32-34]. The theoretical basis for this involves the transfer of heat through convection and radiation from the fire to the pan, as well as the gasification/pyrolysis process in the biomass layer that is affected by the heating rate, oxygen availability, and physical characteristics of the fuel.

Densification of biomass into briquettes is an important step in increasing energy density, uniformity, and ease of handling fuel. Theoretically, increasing compaction pressure can increase the density as well as the mechanical strength of the briquettes, reduce the open porosity, and affect the diffusion of oxygen into the particles. This will have an impact on the combustion rate and heat release pattern. Recent research on briquettes and biochar shows that factors such as compaction pressure, adhesive type and content, and carbonization rate have a direct influence on calorific value, mechanical resistance, and emissions during the combustion process [35]. In briquettes that have holes (holeys or donuts), the addition of an air duct in the middle of the briquette serves to increase the surface area of the reaction and support airflow through the briquette core. Thus, it can theoretically increase the combustion power and improve the temperature distribution within the stove when combined with the right combustion chamber design.

The development of composite fuels through co-pyrolysis or co-combustion of biomass combined with waste oil, such as used cooking oil or other hydrocarbon fractions, is based on the principle of thermochemical synergy between solid and liquid fractions. Waste oil generally has a higher calorific value as well as greater volatility compared to biomass. Therefore, when this material is added in the form of drops or mixtures, it can increase the flame intensity, speed up the ignition process, and modify the distribution of pyrolysis products. Various studies on co-pyrolysis have shown that the addition of liquid or plastic hydrocarbon fractions to biomass can increase the proportion of high-energy products and improve the quality of the liquid or solid fuels produced [36, 37]. In the context of stove use, the injection of used oil in the flame zone can be considered a special example of co-combustion. In this case, the flow of oil droplets serves as an additional source of fuel that is able to increase temperature and firepower. But theoretically, this can also have an impact on emissions and flame stability if not managed properly.

The performance of biomass stoves is assessed based on a number of standard parameters, including thermal efficiency, usable energy, firepower, specific fuel consumption, and pollutant gas emissions. Theoretically, thermal efficiency is defined as the ratio between the energy absorbed by water (the increase in the enthalpy of water in the pot) and the chemical energy of the fuel used. Water Boiling Test (WBT) protocol to standardize efficiency, fuel consumption, and emissions under controlled laboratory testing conditions [38, 39]. Sensitivity analysis conducted in various studies shows that changes in test parameters, such as water volume, use of pot lids, and cold/hot start conditions, can affect the measured efficiency value. Therefore, for the purpose of comparison between briquette density and mode of operation (no vs with waste oil injection), it is necessary to apply a consistent test protocol so that the results can be accurately interpreted in the context of biomass stove performance theory.

3. MATERIALS AND METHODS

3.1 Materials and sample preparation

The main material used in this study is bus wood waste (*Melaleuca viridiflora*), which was obtained from secondary forests in Merauke, South Papua. This species, known by its local name Bus Wood, is part of the Melaleuca community that dominates the Wasur-Merauke landscape, an area rich in biodiversity and has an important role in local ecosystems [40, 41]. Buschwood itself is known as one of the most useful sources of raw materials, especially because it has a high content of lignocellulose as well as a fairly good calorific value, making it one of the potential biomass fuels for use in a wide range of renewable energy applications [42, 43].

Before further utilization, the collected bus wood samples are processed into sawdust, which is an important step in preparing the material for the next stage. This process is carefully carried out to ensure that the quality of the resulting powder meets the required standards. After that, the bus wood powder is dried in the sun for three consecutive days. The purpose of this drying process is to lower the moisture content in the wood powder so that the final moisture content can be ensured to be below 10%. Effective reduction in moisture content is essential as it can affect the combustion efficiency and quality of the briquettes produced.

After the drying process is complete, the finished bus wood powder is put into a doughnut-shaped mold. This molding process is carried out using a hydraulic press equipped with pressure variations of 3, 4, and 5 MPa. The selection of the design of donut briquettes with a hole in the middle was not done arbitrarily, but was based on a number of scientific findings that show that this shape can significantly improve airflow as well as combustion efficiency in biomass furnaces. In addition, this innovative design of briquettes also allows for the reduction of emissions generated during the combustion process, which is one of the important aspects in the development of environmentally friendly energy technologies [44-46] Thus, the research not only focuses on the utilization of bus wood waste, but also seeks to contribute to the development of more sustainable and efficient energy solutions.

3.2 Pyrolysis stove design and instrument

This pyrolysis stove is designed with four layers in a vertical cylindrical configuration. The bottommost layer is called part A, followed by part B as the second layer from the bottom, and part C, which is the third layer from the bottom. These three layers (A, B, C) are the places to place the donut briquettes. The top layer is only partially filled with sand.

This multi-level design implements the fixed-bed downdraft principle, which is often used in laboratory reactors; this helps maintain high-temperature areas along hot gas paths and results in more stable and consistent thermal performance [47-52].

Nine thermocouple sensors are installed strategically in this stove. Three sensors are placed in the lower layer (part A), namely T1, T2, and T3; the other three are in the middle (part B), namely T4, T5, and T6; while the last three sensors are installed in the top layer (part C), namely T7, T8, and T9. All of these thermocouples are connected to a multichannel data logger that records the temperature every two minutes. A schematic diagram of the stove design can be seen in Figure 1.

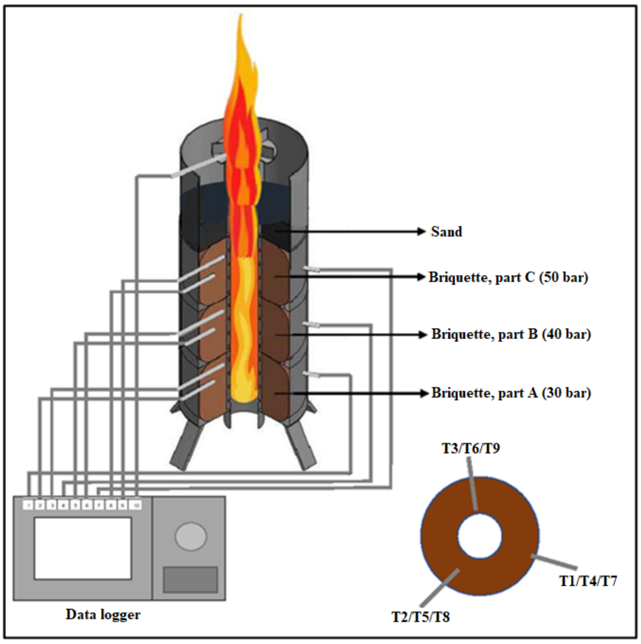

Figure 1. Biomass pyrolysis stove scheme with T1–T9 sensor position

3.3 Experimental procedure

Each condition tested, both without waste oil injection and with used oil injection, underwent three tests to ensure the consistency of the data obtained [53]. This testing process is designed to ensure that the results obtained are accurate and reliable, thus providing a clear picture of the effect of each condition on the final result.

The carefully prepared donut briquettes are then placed in a stove that has been set up for this experiment. The stove is lit using a burner as an initial trigger to start the pyrolysis process. During the course of the experiment, the temperature measured from the nine precisely installed thermocouple points is automatically recorded by the monitoring system, while the changes in the color of the flames that appear during the process are visually observed to obtain additional information about the reactions that occur.

After the pyrolysis process is completed, the resulting biochar is carefully removed from the reactor and cooled in a sealed container to prevent unwanted oxidation. After the cooling process is complete, the biochar products resulting from the pyrolysis are weighed using accurate scales, and the yield is calculated based on the mass of the initial material used in this experiment. This yield calculation is very important to evaluate the efficiency of the pyrolysis process that has been carried out. This method follows standard procedures for biomass pyrolysis that have been described in detail by various researchers, including [54-57]. These studies provide valuable guidance in understanding and properly implementing the pyrolysis process, as well as aid in the development of more efficient and environmentally friendly techniques in biomass processing.

3.4 Data analysis

The data analysis in this study focuses on two important aspects, namely the energy rate and the temperature profile produced during the combustion process. Energy rate is one of the key parameters in assessing the efficiency of using energy sources, while temperature profiles provide detailed information about the temperature distribution during the process.

To calculate the energy produced, the WBT method is used, which has been widely recognized as a standard technique for evaluating the performance of biomass stoves. This method not only provides accurate results but also allows comparisons between the different types of biomass stoves on the market [34, 58].

In energy calculation, Eq. (1) is used as the basis for calculation. This equation is designed to provide an accurate estimate of the amount of energy produced during the test, so that the results of this analysis are expected to provide insight into the biomass stove being studied:

$$Q = m \times c \times \Delta T \tag{1}$$

where:

$Q = Energy\ (J)$

$m = water\ mass\ (kg)$

$c = specific\ heat\ of\ water\ \left(4186 \frac{J}{kg}\right)$

$\Delta T = 100 - 28 = 72\ ℃$

Proximate analysis was performed to determine the content of moisture, ash, volatile substances, and solid carbon, referring to the standard (ASTM D3173/D3174/D3175/D3172), high calorific value (HHV) measured using the ASTM D5865 standard bomb calorimeter [59-61].

4. RESULT AND DISCUSSION

This study aims to conduct a proximate analysis and performance of biomass pyrolysis stoves. The main focus of this study is to explore the temperature profile generated during the pyrolysis process, as well as the rate of energy that can be produced, both under conditions with and without the injection of used oil in the arrangement of donut briquettes (A, B, C) with densities of 30 bar, 40 bar, and 50 bar.

By comparing the two conditions, it is hoped that this study can provide broader insights into the effect of briquette density and waste oil injection on the performance of pyrolysis stoves, as well as provide useful recommendations for the development of biomass-based renewable energy technology in the future.

4.1 Result

The results of proximate testing on bus wood waste showed a moisture content of 10.83%, ash content of 1.79%, volatile 67.89%, fixed carbon 19.49%, and a calorific value of 4,446 cal/g. The high content of volatile matter indicates good thermal reactivity, while the low moisture and ash content generally support combustion efficiency and reduce fouling. Biomass with higher volatile matter and fixed carbon, accordingly, shows better thermal behavior [62, 63]. Tropical hardwoods often display HHVs in the range of 19-22 MJ/kg when moisture and ash contents are minimized [63, 64], placing the bus wood energy quality in a comparable class.

Table 1. Results of lignocellulose content

Biomass	Hemicellulose (%)	Cellulose (%)	Lignin (%)
Bus Wood Waste	20.61	40.28	31.62

Table 2. Results of proximate testing of bus wood waste

Biomass	Moisture (%)	Ash (%)	Volatile (%)	Fixed Carbon (%)	HHV (cal/g)
Bus Wood Waste	10.83	1.79	67.89	19.49	4,446

To assess the position of bus wood as a biomass fuel, these results were compared with several other types of biomass that have been extensively researched.

Table 3. Comparison of the proximate analysis of several types of biomass

Biomassa	Moisture (%)	Ash (%)	Volatile (%)	Fixed Carbon (%)	HHV (cal/g)
Bus wood	10.83	1.79	67.89	19.49	4,446
Rice husk	12–15	15–20	60–65	10–15	3,200–3,800
(EFB) of oil palm	8–12	3–6	70–75	15–18	4,200–4,500
Tropical Hardwood	8–12	1–3	65–70	18–22	4,500–4,800
Corn Cob residue	10–14	4–6	68–72	14–18	4,000–4,300

Note: Bus wood: Result; Rice husk: [65-67]; EFB of oil palm: [68]; Tropical Hardwood: [64, 69]; Corn Cob residue: [70].

From Tables 1-3, Figure 2, and Figure 3, it is evident that the properties of bus wood closely resemble those of tropical hardwood biomass. The relatively low levels of moisture and ash suggest its appropriateness for combustion and pyrolysis applications. Furthermore, the high volatile matter content of bus wood, measured at 67.89%, indicates excellent thermal reactivity. This figure is comparable to certain agricultural biomasses, including corn cob, which has been reported to have approximately 68%–72% volatile matter, around 4%–6% ash content, and a higher heating value (HHV) of about 18.00 MJ/kg (4,300 cal/g) [68]. In contrast, rice husks typically contain higher ash levels (15%–20%), which increase the risk of fouling and slagging. Meanwhile, several tropical hardwoods exhibit volatile matter in the range 65%–70% and calorific values between 18.84–20.09 MJ/kg (4,500–4,800 cal/g), confirming that bus wood has energy quality comparable to other hardwood species [64, 69].

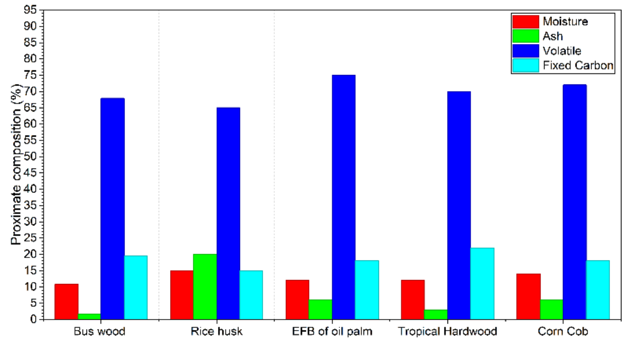

Figure 2. Comparison of the proximate composition of several biomass

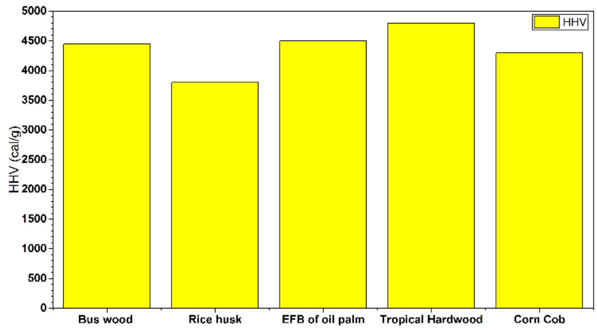

Figure 3. Comparison of calorific values of some biomass

The calorific value of bus wood (4,446 cal/g) puts it in the middle to upper-middle position in the biomass classification. This value is higher than rice husks, but slightly lower than tropical hardwood. This can be explained by the fairly high lignin content of bus wood (31.62%), contributing to long-term energy during combustion.

The following is a graph of the temperature distribution of test results (Figures 4-12).

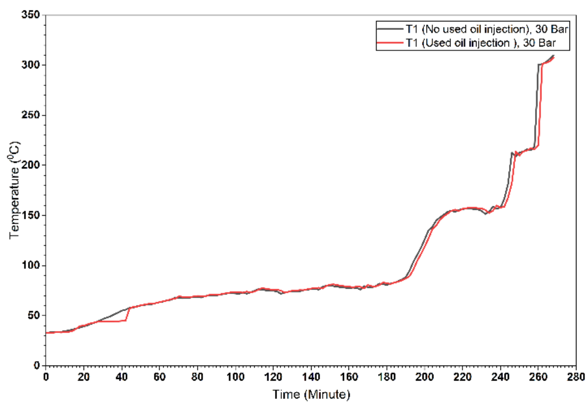

Figure 4. Temperature distribution (T1) on the pyrolysis stove

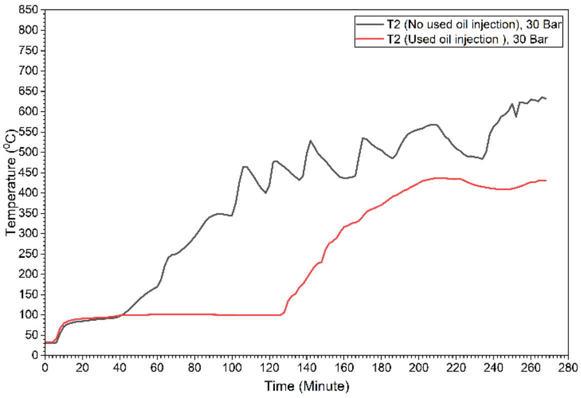

Figure 5. Temperature distribution (T2) on the pyrolysis stove

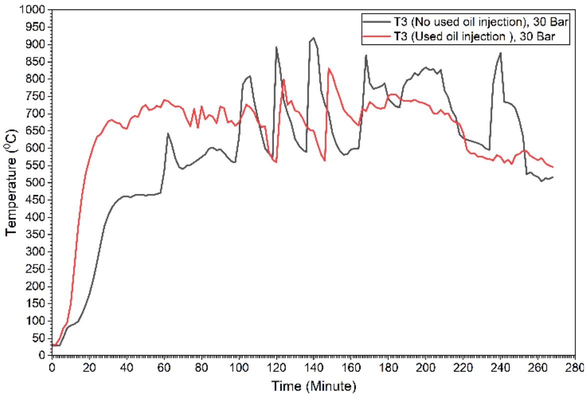

Figure 6. Temperature distribution (T3) on the pyrolysis stove

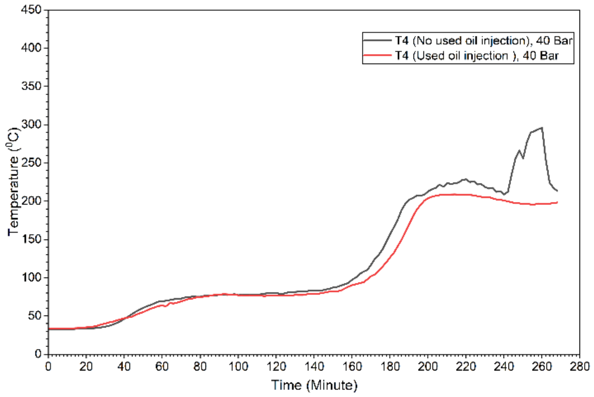

Figure 7. Temperature distribution (T4) on the pyrolysis stove

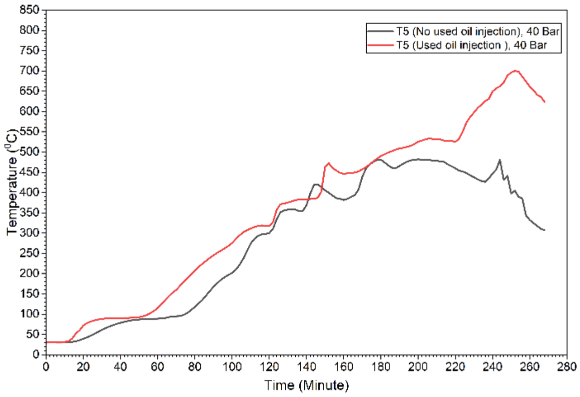

Figure 8. Temperature distribution (T5) on the pyrolysis stove

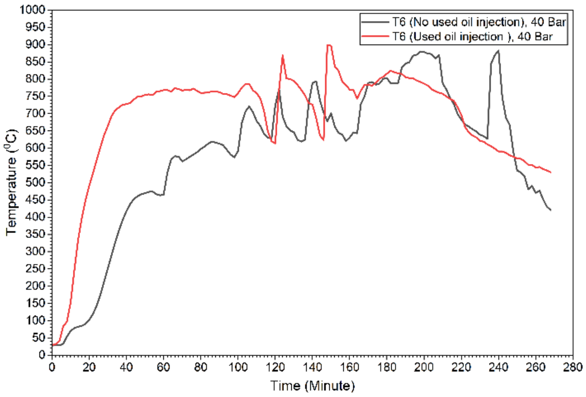

Figure 9. Temperature distribution (T6) on the pyrolysis stove

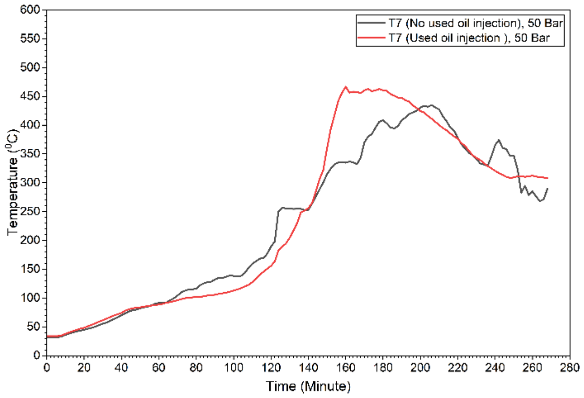

Figure 10. Temperature distribution (T7) on the pyrolysis stove

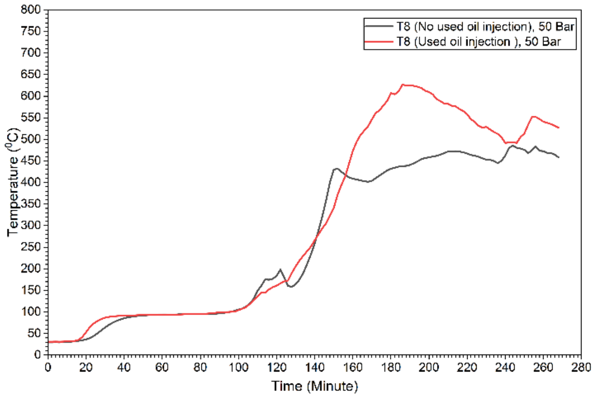

Figure 11. Temperature distribution (T8) on the pyrolysis stove

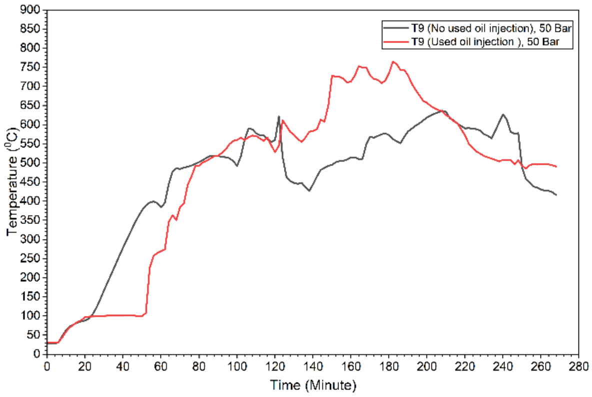

Figure 12. Temperature distribution (T9) on the pyrolysis stove

4.1.1 Temperature profile on briquettes density 30 bar (T1–T3)

Based on Figures 4-6, with a density of 30 bar, the temperature development on the outer edge of the briquettes (T1) shows a gradual rise from about 30–40 °C at the beginning of the test to about 150–170 °C at the 220th minute, then a sharp increase near 300 °C towards the end of the process. The temperature curve for conditions without and with the injection of used oil is almost constant all the time, so that in the outer edge zone, the effect of the addition of used oil on the temperature is relatively small. This pattern corresponds to the character of a fixed-bed stove where the main reaction zone is in the core part of the bed, while the part near the wall tends to be at lower temperatures [71, 72].

The middle radial temperature profile (T2) shows a clearer difference between the two treatments. Without the injection of used oil, the temperature rises relatively quickly after the initial heating phase, reaching about 250 °C at the 70th minute and continuing to rise to the range of 450–500 °C with some local fluctuations, before approaching 600–650 °C. With used oil injection, the temperature rise in the same position is held longer; The T2 curve flattens at around 90–110 °C until about the 120th minute, only then gradually increases and persists in the range of 380–420 °C until the end. This suggests that at low densities, the addition of waste oil tends to lower the maximum temperature in the central zone and prolong the heating phase, although the temperature remains within the commonly reported biomass slow pyrolysis range [73, 74].

In the position of the inner edge bordering the central hole of the briquette (T3), both treatments produced the highest temperature compared to T1 and T2. Without the injection of used oil, the temperature of the T3 rises gradually and only reaches 450–500 °C after the 60th minute, then shows some sharp peaks that can approach 800–900 °C before slowly decreasing. With used oil injection, the temperature rise of T3 is much faster; within ±20 minutes after start-up, the temperature has already passed 600 °C and then persists in the range of 650–700 °C with more subtle fluctuations. This temperature range of 600–800 °C is consistent with the reactor core conditions in pyrolysis and gasification of high-energy biomass [35, 73].

4.1.2 Temperature profile on briquettes density 40 bar (T4–T6)

Based on Figures 7-9, with a medium density (40 bar), the outer edge sensor (T4) again shows the lowest temperature among the three radial positions. Without the injection of used oil, the temperature of the T4 increases from about 30–40 °C to 70–80 °C in the 60th minute, then gradually reaches 200–220 °C and peaks at around 280–300 °C. With used oil injection, the curve shapes similarly, but the peak is slightly lower, around 190–210 °C, with no sharp spikes at the end. This indicates that in the outer edge zone, the addition of used oil tends to dampen the rise in peak temperatures and produce a smoother heating profile, in line with the finding that changes in fuel composition more predominantly affect the core zone of the reactor [71, 75].

The difference in the effect of used oil injection is clearly visible on the central radial sensor (T5). Without oil injection, the temperature rises gradually to about 450–500 °C and then decreases slightly towards the end. With oil injection, the temperature rise after the 120th minute becomes faster and continues until it reaches the range of 650–700 °C before descending; The average temperature in this zone is higher overall than in pure biomass mode. This increase is consistent with the concepts of co-combustion and co-pyrolysis, where the addition of a fraction of high-calorific liquid fuel can increase flame intensity and local temperature [27, 76].

The inner-edge sensor (T6) at a density of 40 bar records the highest temperature value in layer B. Without oil injection, the temperature rises slowly, only exceeding 400–500 °C after the 60th minute and subsequently showing peaks that can approach 850–900 °C. With used oil injection, the temperature rises much faster; in ±20–30 minutes, the temperature has been in the range of 650–750 °C and has remained relatively stable within that range before declining. This confirms that at medium density, the injection of used oil accelerates the achievement of high core temperatures and reduces the amplitude of peak temperature fluctuations, which is in line with the results of the model and co-combustion experiments of oil on biomass-based systems [27, 75].

4.1.3 Temperature profile on briquettes density 50 bar (T7–T9)

Based on Figures 9-12, at the highest density layer (50 bar), the temperature at the outer edge (T7) increases from about 30–40 °C to almost 200 °C at about 120 minutes, then rises sharply to the range of 400–450 °C before declining. With used oil injection, the T7 temperature rise is initially slightly delayed, but subsequently the curve with oil goes beyond the oilless curve and reaches a peak of about 450–470 °C, with a more sloping descent. This shows that at high density, the influence of co-fuel begins to be felt even in the outer edge zone, as the heat distribution inside the bed is more uniform.

In the middle radial (T8), the differences between treatments become more pronounced. Without oil injection, the temperature rises to about 400–450 °C and persists in this range with little fluctuation. With oil injection, the temperature rises faster after the 130th minute and peaks at about 600–630 °C, then gradually decreases but remains above the oilless curve for most of the rest of the test. This increase in temperature at the highest density is in line with reports that high-density briquettes with a compact structure can maintain a more intense flame when combined with high-calorific liquid fuels [77, 78].

The inner edge sensor (T9) shows the highest temperature in layer C. Without oil injection, the temperature rises rapidly to 550–600 °C around the 100th minute and then fluctuates in the range of 500–650 °C. With used oil injection, the temperature rise is slightly delayed at the beginning, but after the 120th minute, the curve continues to rise until it reaches around 730–760 °C before slowly dropping towards the 500 °C range. The high core temperature range and longer duration of the temperature plateau in the waste oil treatment indicate the presence of a significant additional energy supply in the main reaction zone, consistent with the characteristics of biomass–oil co-pyrolysis and co-combustion reported in the literature [27, 74, 76].

4.1.4 Radial gradient patterns and effects of density–injection combination of used oil

Overall, the entire treatment combination showed a consistent radial temperature gradient, where the inner edge sensor (T3, T6, T9) always recorded the highest temperature, followed by the middle radial (T2, T5, T8), while the outer edge (T1, T4, T7) had the lowest temperature. This pattern is consistent with the characteristics of fixed-bed reactors and cylinder gasifier stoves, where the dominant oxidation and pyrolysis zones are near the fuel core and produce higher temperatures than the outer walls [71, 79].

In terms of density, an increase in compaction pressure from 30 to 40 and 50 bar tends to raise the maximum temperature and prolong the duration of high temperatures in the middle and deep radial positions, especially in treatment with used oil injection. This is consistent with the results of densification studies, which report that higher density briquettes generally result in more stable combustion, more uniform fire temperatures, and longer flame durations, although the total combustion rate decreases [23, 35, 78].

Regarding the effect of used oil injection, the results showed that the effect depended on the combination of density and radial position. At a density of 30 bar, waste oil mainly increases the temperature in the core (T3) but tends to decrease or delay the temperature rise in the middle radial (T2). At densities of 40 and 50 bar, oil injection consistently increases the temperature in the middle radial and core (T5, T6, T8, T9), accelerates the achievement of high-temperature plateaus, and dampens temperature spikes on the outer edges. This pattern is in line with the basic principles of co-combustion and co-pyrolysis, in which the addition of oil fractions increases flame intensity and local temperature, while modifying the heat distribution within the reactor [27, 75, 80].

4.1.5 Energy calculation using the Water Boiling Test (WBT)

Stove performance measurement is carried out by WBT, where energy is expressed as the rate of useful energy (MJ/h) transferred to the water in the pot. This method is widely used to compare the heat transfer efficiency between biomass stove designs in the laboratory and field [58].

Example of energy calculation using the WBT method: In the first test (no used oil injection) to heat water by 2 kg (initial temperature 28 °C) until it boils, it takes 9.58 minutes, then the energy rate per hour is calculated as follows: Eq. (2). Table 4 shows a table of observations and the results of the calculation of energy rates.

$$Energi\ per\ hour = \frac{Q}{t} \times 60 \quad (2)$$

where:

$$Q = m \times c \times \Delta T$$
$$Q = 2 \times 4186 \times (100 - 28)$$
$$Q = 602784\,J = 0.6028\,MJ$$

so:

$$Energi\ per\ hour = \frac{Q}{t} \times 60$$
$$Energi\ per\ hour = \frac{0.6028}{9.58} \times 60 = 3.77$$

The results of the WBT test (Figure 13) of 16 times show that the Kayu Bus briquette pyrolysis stove is able to produce relatively stable useful energy, both in operation without or with the injection of used oil. The hourly useful energy value is in the range of about 3.7–4.2 MJ/hour for non-injection conditions and around 3.8–4.3 MJ/h for conditions with used oil injection. The fluctuations between repetitions are relatively small; the energy value spread in each test mode was generally less than ±0.2 MJ/hr of its average inclination, indicating that the stove-briquette system performed fairly repeatably throughout the test series, in line with the performance stability findings of the stove gasifier and TLUD tested using WBT and ISO 19867-1 protocols [38, 58, 71].

In general, the energy curve is useful for conditions with used oil injection (red line) being slightly above the no-injection curve (black line) on most test numbers. In the initial test (1st to 7th test), the difference between the two curves was relatively consistent: The useful energy with oil injection was about 0.05–0.2 MJ/hour higher than without injection. This shows that the addition of waste oil as a co-fuel is able to increase the utilization of heat energy from the pyrolysis process without disturbing the stability of stove operations, consistent with reports that the addition of a fraction of high-calorific liquid fuel can increase firepower and clean heat output in biomass conversion systems [27, 76].

Table 4. Time observation and energy rate calculation results

Test Number	Time (Minute)		Energy per hour (MJ/hr)	
	No Used Oil injection	Used Oil Injection	No Used Oil Injection	Used Oil Injection
1	9.58	9.33	3.77	3.88
2	9.62	9.12	3.76	3.96
3	9.23	8.84	3.92	4.09
4	9.31	8.90	3.89	4.06
5	9.28	8.87	3.90	4.08
6	9.40	9.13	3.85	3.96
7	9.32	9.03	3.88	4.00
8	9.16	9.58	3.95	3.77
9	8.77	8.47	4.12	4.27
10	9.16	9.41	3.95	3.84
11	8.96	9.38	4.04	3.85
12	9.41	8.87	3.85	4.08
13	8.90	8.82	4.06	4.10
14	9.31	9.43	3.88	3.84
15	9.36	9.26	3.86	3.91
16	8.72	8.86	4.15	4.08

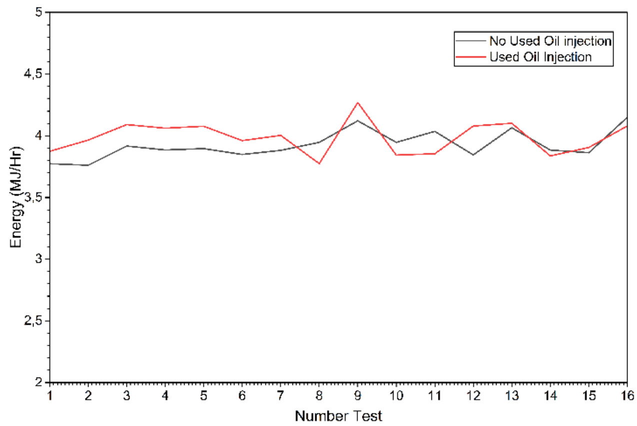

Figure 13. Result Water Boiling Test (WBT)

In the mid-to-late tests (8th to 16th tests), the two curves showed a pattern of approximation, although at some test points (e.g., 9th and 13th tests), conditions with oil injection still provided slightly higher peak useful energy values than without oil. On the other hand, there are some repeats (e.g., the 8th and 10th tests) in which the useful energy with the oil injection drops close to or slightly below the conditions without oil, which indicates the presence of sensitivity to small variations in operating parameters, such as the rate of oil droplets or the distribution of briquettes. This phenomenon of inter-test variability is consistent with the sensitivity analysis of WBT and biomass stove test parameters reported in the literature, where small changes in test conditions can affect estimates of efficiency and useful energy [38, 81].

Overall, there was no systematic decline in performance from the first to the last repeat; both operating conditions maintained useful energy values in the range of 3.8–4.1 MJ/h with relatively narrow variations. This confirms that the combination of multilayer pyrolysis stoves and Bus Wood donut briquettes is capable of providing stable heat output in repeated use scenarios, and that the injection of used oil provides a small but consistent addition of useful energy. This energy range is within the range of efficient biomass stove performance reported in WBT studies and household stove performance tests in developing countries, suggesting that the stove-fuel configuration in this study is at a competitive level of performance for domestic cooking applications [71, 72, 79].

4.2 Discussion

The temperature distribution recorded at the nine measurement points (T1–T9) showed a consistent radial gradient in the annular pyrolysis reactor. The highest temperature was observed on the inside side of the briquettes (T3/T6/T9), followed by the middle (T2/T5/T8), while the outer side (T1/T4/T7) remained at the lowest temperature range. This pattern corresponds to the characteristics of fixed-bed downdraft, where intensive reaction zones typically form near hot gas flow channels and flame fronts, while the outer layer functions more as a thermal insulator [58, 79]. The maximum temperature reached inside, ranging from 800–900 ℃, suggests that the reactor can create pyrolysis conditions that are close to the high-temperature char production regime, which is important for the formation of high-quality biochar as well as tar decomposition [35, 82].

The impact of briquette density on the temperature profile becomes very clear when comparing layers A (30 bar), B (40 bar), and C (50 bar). At low pressure (30 bar), heating occurs more quickly on the inside, but temperature fluctuations are quite significant, especially at the T3 point, which reflects a shift in the fire front and variations in the rate of devolatilization. Meanwhile, at pressures of 40 and 50 bar, the increase in temperature at the T5/T6 and T8/T9 points takes place more gradually, but results in a more stable temperature plateau in the range of 650–800 ℃. These findings are in line with densification theory, which states that increased compaction pressure can shrink macro pores, improve interparticle interactions, and increase thermal conductivity. As a result, the movement of the pyrolysis front becomes more regular, and the combustion process becomes more stable [35, 83]. On the other hand, the temperature at the outer point (T1/T4/T7) remains below 300–320 ℃ for most of the process. This suggests a significant radial conduction gradient and reinforces the hypothesis that the briquette edge serves as an insulating "blanket" that reduces heat loss through convection to the reactor wall [58, 84].

A comparison between treatment with and without the injection of used oil showed that the effect of co-fuel was greatly influenced by the location of the thermocouple as well as the density of the briquettes. At a density of 30 bar, the injection of used oil slightly increases the rate of temperature rise at T1 and T3 in the early stages of the process. However, in T2, it actually produces a lower temperature with a smoother curve than the condition without injection. These findings indicate that the addition of oil can enrich the volatile phase and increase local heat capacity. On the other hand, it also has the potential to slow down oxidant diffusion as well as move the main reaction zone to the inside of the briquettes, thus causing the temperature in the middle zone not to reach the same level as in the case without the use of oil [85, 86]. The same trend—the acceleration of the heating process and the increase in core temperature—is observed more clearly at pressures of 40 and 50 bar, where the addition of oil causes the temperature to rise at the midpoint and depth (T5/T6 and T8/T9) to tens of degrees. This increase is mainly seen in the early to middle phase of pyrolysis, before gradually decreasing in the late phase due to reduced volatile content [27, 87].

These findings are consistent with research on co-pyrolysis between plastic waste and oil, which shows that the presence of oil can accelerate heat transfer, increase the rate of temperature rise, and support the formation of liquid and gas fractions with high calorific values through synergistic interactions between hydrocarbon components [27, 85]. However, when the effective porosity is too low as a result of the high density, the pyrolysis and oil results can be trapped. This leads to the formation of very local reaction zones with sharp temperature fluctuations, as seen at some peaks in the T3, T6, and T9 curves. A similar phenomenon has also been reported in high-pressure biomass briquettes, where a combination of high density and limited air supply can trigger periodic transitions between exothermic and endothermic reactions in the bed [35, 84].

Although the internal temperature gradient is quite extreme, the WBT test results show that the useful energy delivered to the pan is in a relatively narrow range, around 3.5–4.1 MJ/hr for all test variations, with the used oil injection providing an average increase of only about 0.1–0.2 MJ/hr. This suggests that most of the additional energy from the waste oil is channeled to accelerate internal pyrolysis and the formation of gaseous/liquid products, rather than directly increasing heat transfer to the water load [79, 88]. This condition is in line with research on WBT tests, which show that modifications to stove design or fuel characteristics do not necessarily result in significant improvements in thermal efficiency. This is due to several factors, such as the limitation of heat transfer areas, heat loss through walls, and fire instability, which is often the main barrier [58, 89].

Based on the comparison with the pyrolysis stove performance range described in the systematic review, the useful energy values obtained from this study were moderate but showed relatively consistent stability of both treatments [79, 81]. This stability is important from the perspective of the household user, since the variation in low useful energy is directly related to the ability to predict cooking time and comfort in operation, although the maximum level of efficiency has not yet been achieved. Previous research on biomass stoves using agricultural waste has also indicated that a combination of a reactor design that concentrates heat in the central area and the application of a high-density fuel can produce a more stable flame, albeit with only moderate WBT efficiency [35, 79].

Overall, the results of this study show that the use of medium to high density (40–50 bar) Bus donut briquettes combined with waste oil injection is more effective in creating a hot and stable pyrolysis environment in the reactor core. It provides benefits in the process of converting biomass into high-quality biochar and gas. However, the improvements obtained in cooking performance, measured through the WBT method, are limited. These findings support recent recommendations regarding the use of briquette-based stoves in developing countries, which suggest that the design of the technology should integrate two main objectives: efficiency in cooking and the production of value-added biochar, especially when utilizing biomass as well as local waste [35, 58].

From a systems engineering perspective, these findings open up opportunities for further development, for example, by optimizing the ratio of waste oil injection rate to airflow, increasing the heat transfer surface area above the reactor, and integrating emission measurements (CO, PM, and volatile organic compounds) to assess the trade-off between increased core temperature and potential increased emissions. The application of the latest ISO-based testing protocols and temperature distribution numerical modeling approaches will help to refine the stove design so that thermal and environmental performance can be improved simultaneously [58, 81].

5. CONCLUSIONS

1) The temperature distribution inside the reactor shows a clear radial gradient, with the highest temperature at the briquette edge (T3, T6, T9) and the lowest at the outer edge (T1, T4, T7). The design of the multilayer annular reactor with donut briquettes effectively concentrates pyrolysis and combustion, favoring the formation of biochar and high-heat gases without overheating.
2) The density of Bus Wood briquettes affects the stability of pyrolysis. Low-density briquettes (30 bar) heat up faster, but the temperature fluctuations are greater. Medium to high density (40–50 bar) results in a stable temperature plateau of 650–800 ℃, reflecting better pyrolysis control.
3) Injection of used oil as an effective co-fuel for medium to high density briquettes. At densities of 40 and 50 bar, the injection increases the maximum temperature and accelerates the plateau in the central zone. However, at low density, the temperature in the central zone is lower even though the core is elevated, indicating a change in the reaction zone.
4) The increase in core temperature due to the injection of used oil does not completely improve cooking performance. The useful energy during WBT testing ranges from 3.7–4.2 MJ/hour, with an increase of 0.1–0.2 MJ/h from waste oil, which is used more to speed up pyrolysis than to increase heat transfer.
5) The best stove-fuel combination is a 40–50 bar density Wood Bus donut briquette with used oil injection. This combination results in stable pyrolysis and consistent energy output, as well as utilizing solid and liquid waste for the supply of heat energy and biochar production.
6) Development recommendations: To optimize cooking efficiency and emissions, further research is recommended to: (i) explore variations in oil injection rate and air ratio; (ii) expand the heat transfer area; and (iii) measure emissions of CO, particulates, and volatile organic compounds, in order to design a better Kayu Bus pyrolysis stove for renewable energy technology in South Papua.

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NOMENCLATURE

Q	energy, J
m	water mass, kg
c	specific heat of water, 4186 J/kg
ΔT	temperature difference, °C