P-ISSN: 2987-7261
E-ISSN: 2987-7253

Jurnal Riset Ilmu Teknik
Journal homepage: https://jurnaljepip.com/index.php/jurit
Vol 4, No. 1, pp. 1-11, 2026

An Experimental Study of the Effect of Wood Fuel Variations on Biomass Stove Performance

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ABSTRACT

The performance of biomass stoves is influenced by fuel characteristics and operating conditions, including wood species and fuel mass. This study investigated the effects of wood species and initial fuel mass on the fuel consumption rate, thermal power, and thermal efficiency of a steam-injection biomass stove. Three wood fuels pine, fir, and coffee wood were tested at initial masses of 0.8, 1.0, and 1.2 kg, resulting in nine experimental conditions. The steam injector was supplied with 750 mL of water in each test. Stove performance was evaluated using the Water Boiling Test with 3 L of water at an initial temperature of 25°C. Fuel consumption, boiling duration, temperature, remaining fuel, charcoal, and water mass were recorded to calculate the fuel consumption rate, thermal power, and thermal efficiency. The results showed that increasing the initial fuel mass was accompanied by increases in fuel consumption rate and thermal power but decreases in thermal efficiency for all tested wood species. The highest fuel consumption rate and thermal power were observed with 1.2 kg of pine wood, reaching 0.0013 kg/s and 9.07647 kcal/s, respectively; however, its thermal efficiency was approximately 13%. In contrast, the highest thermal efficiency of 20% was obtained using 0.8 kg of fir wood. These findings demonstrate a trade-off between maximum heat output and efficient fuel-energy utilization. Under the tested conditions, pine wood at 1.2 kg was more suitable when high thermal output was prioritized, whereas fir wood at 0.8 kg provided the most favorable thermal efficiency. Further replicated experiments and statistical analyses are required to confirm the effects of wood species, fuel mass, and their interaction.

Keywords: *Biomass Stove, Overfire Injection, Wood Fuel, Combustion Efficiency, Renewable Energy*

Manuscript received 12 February. 2026; revised 5 March. 2026; accepted 23 Apr. 2026.

INTRODUCTION

The global energy crisis and growing awareness of the importance of sustainable environmental management have encouraged the world to seek environmentally friendly and renewable energy alternatives [1], [2]. Amid the dominance of fossil fuels such as petroleum, coal, and natural gas, biomass has emerged as one of the renewable energy sources with significant potential for development, particularly in developing countries such as Indonesia. Biomass refers to organic materials derived from plants, animals, and organic waste that can be used as fuel through various energy conversion processes, one of which is direct combustion in biomass stoves [3], [4].

Among the various types of biomass, wood is one of the most commonly used solid biomass fuels due to its abundant availability, ease of processing, and relatively high calorific value. The use of wood as a fuel source has been practiced for centuries and has continued to develop in terms of combustion technology [5], [6], [7]. However, the main challenges associated with wood fuel are low combustion efficiency and the resulting emissions, particularly when combustion is incomplete. Therefore, innovative combustion technologies are needed to improve efficiency and reduce emissions, one of which is the use of an overfire air injection biomass stove [8], [9], [10].

An overfire air injection biomass stove is a combustion technology that employs a secondary air supply from above the primary combustion zone (overfire air) to ensure further combustion of unburned gases generated during the initial combustion process [11], [12]. This system enables more complete combustion, produces more stable heat, and reduces emissions such as carbon monoxide (CO) and unburned hydrocarbons. This type of stove is particularly suitable for rural areas because of its simple construction, relatively low cost, and compatibility with various types of biomass fuels, particularly locally available wood [13], [14], [15].

Nevertheless, the performance of a biomass stove is strongly influenced by the type of wood fuel used. Each type of wood has different physical and chemical characteristics, including density, moisture content, calorific value, and combustion rate [16], [17], [18]. For example, hardwood such as teak (Tectona grandis) generally has a higher calorific value and density than lightweight wood such as sengon (Paraserianthes falcataria), resulting in a more stable and longer-lasting flame. In contrast, lightweight wood tends to burn more rapidly but produces less heat. Therefore, selecting an appropriate wood species is essential for determining the efficiency and performance of a biomass stove [19], [20], [21].

This study is expected to provide a scientific contribution to the development of biomass stove technology, particularly in terms of utilizing wood fuels more efficiently and sustainably. In addition, the findings are expected to serve as a reference for communities, small-scale industries, and government agencies in determining the most suitable type of fuel for use in overfire biomass stove systems, particularly in supporting locally based clean energy programs. Through a systematic and experimental data-driven approach, this study will address the extent to which variations in wood species affect combustion performance and the efficiency of biomass stoves.

MATERIALS AND METHOD

The research was conducted from July to August 2025 at the Mechanical Engineering Laboratory, Indonesian Christian University of Toraja, North Toraja Regency, and at the Animal Nutrition and Feed Laboratory, Faculty of Animal Science, Hasanuddin University, for determining the heating value of the fuel materials. The test object was an overfire-injection biomass stove equipped with a steam injection system that delivered steam from an injector tank into the combustion chamber, as shown in Figure 1. The stove consisted of a pot stand, combustion chamber, chimney, ash collection chamber, and steam injection system comprising an injector tank, steam control valve, delivery pipe, and injection nozzle that directed steam into the combustion chamber, as illustrated in Figure 2.

Three types of biomass fuel were used in the experiment: fir wood, coffee wood, and pine wood. All wood materials were collected from unused forest residues in the North Toraja area and were dried before testing. The fuel was prepared with dimensions of 4 × 14 cm. The fuel mass variations were 0.8 kg, 1.0 kg, and 1.2 kg for each type of wood, while the volume of injected water was maintained at 750 mL for all treatments.

Figure 1. Overfire-Injection Biomass Stove Used in The Experiment

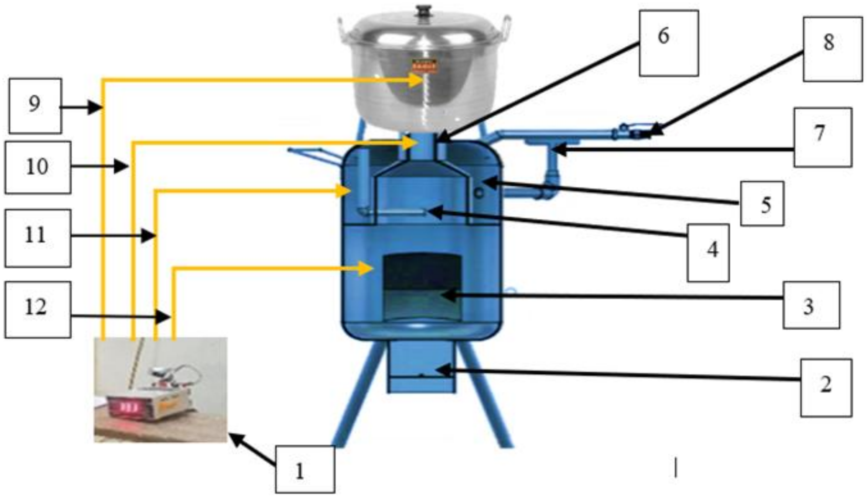

Figure 2. Steam-Injection Stove and Its Components

The components shown in Figure 2 consist of a thermocouple, air inlet, combustion chamber, steam injection nozzle, injector tank, chimney, injector tank inlet, steam control valve, and temperature sensors. The thermocouple is used to measure the water temperature in the pot, the temperature in the stove chimney, the injector water temperature, and the combustion temperature. The air inlet functions to supply oxygen to the combustion chamber, while the combustion chamber serves as the area where fuel combustion takes place. The steam injection nozzle delivers steam into the combustion chamber, whereas the injector tank stores and generates the steam used in the steam injection process. The chimney serves as a passage for discharging combustion gases to the outside environment, while the injector tank inlet is used to fill water into the injector tank. The steam control valve regulates the flow of steam from the injector tank to the injection nozzle in the combustion chamber. The pot water temperature sensor measures the water temperature before it is converted into steam and supplied to the combustion chamber, thereby supporting the efficiency, safety, and stability of the steam injection process. The chimney temperature sensor measures the temperature of the exhaust gases discharged from the biomass stove through the chimney. The injector water temperature sensor measures the temperature of the water inside the injector tank, while the combustion chamber temperature sensor measures the temperature inside the biomass stove combustion chamber in real time.

Figure 3. Pine Wood, Fir Wood, and Coffee Wood Used as Biomass Fuels

The data collection procedure was conducted as follows. The stove performance was evaluated using the Water Boiling Test (WBT) with 3 L of water at an initial temperature of 25°C. The testing procedure generally consisted of the following steps: (a) weighing the fuel according to the predetermined mass variations; (b) filling the injector tank with 750 mL of water; (c) placing the pot containing water on the stove and installing thermocouple sensors on the pot, combustion chamber, chimney, and injector tank; (d) recording the initial temperature at all measurement points before ignition; (e) igniting the fuel while simultaneously activating the timer; (f) recording the temperature at all measurement points and the air flow velocity every minute until the water reached boiling temperature; and (g) weighing the remaining fuel, charcoal, water in the pot, and remaining injected water immediately after the water reached its boiling point.

Each combination of fuel type and fuel mass was tested using an identical procedure to ensure data consistency among treatments. The experimental data were subsequently processed to determine three stove performance parameters, namely the fuel consumption rate (FCR), thermal output power (Pout), and thermal efficiency (ηt), using Equations (1)–(3), [8].

RESULTS AND DISCUSSION

Water Boiling Test

The results of the water boiling test for the nine fuel variations, with a constant injected water volume of 750 mL, are presented in Table 1. The test was conducted to evaluate the performance of the steam-injection biomass stove in terms of the time required to activate the steam injector and the time needed to bring the injected water to boiling conditions. In general, the results indicate that variations in fuel type and fuel mass affected both the activation time of the steam injector and the boiling time of the water. Increasing the amount of fuel used tended to reduce the time required to activate the steam injector because a larger quantity of combustible material provided a greater initial heat supply to the combustion chamber. The higher heat input accelerated the heating process and promoted faster evaporation of water in the injector tank, allowing the steam injector to become operational in a shorter period.

However, the increase in fuel mass was also associated with a longer overall combustion duration and, in several variations, a longer time required to complete the water boiling process. This condition indicates that the amount of fuel affects not only the initial heat generation but also the duration and continuity of the combustion process. A greater fuel mass provides more combustible material, allowing the fire to be maintained for a longer period. The resulting heat is transferred gradually from the combustion chamber to the water, thereby affecting the total boiling time. In addition, differences in the physical characteristics and combustion properties of pine, fir, and coffee wood may contribute to variations in heat release and combustion stability.

The results demonstrate that fuel mass and fuel type are important factors in determining the thermal performance of the steam-injection biomass stove. Although increasing fuel mass can provide a greater energy supply and accelerate steam injector activation, it does not necessarily result in the shortest water boiling time or the most efficient use of fuel. Therefore, selecting an appropriate combination of fuel type and fuel mass is necessary to obtain a balance between rapid steam injector activation, sufficient heat generation, combustion duration, and overall thermal performance. These findings provide an important basis for determining suitable operating conditions for the biomass stove when using different types of wood fuel.

Fuel Consumption Rate

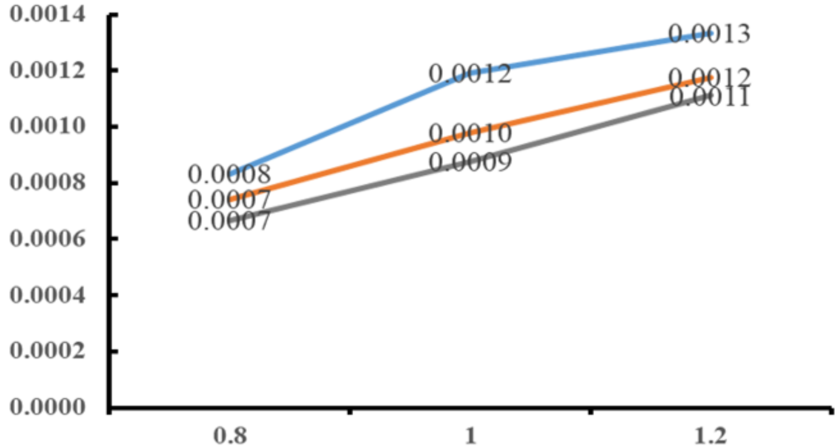

Figure 4. Fuel Consumption Rate (FCR)

Figure 1 illustrates the effect of variations in wood fuel type and fuel mass on the fuel consumption rate (FCR). The results show that both fuel type and fuel mass influenced the rate at which the fuel was consumed during the combustion process. For pine wood, the FCR increased from 0.0008 kg/s at a fuel mass of 0.8 kg to 0.0012 kg/s at 1.0 kg and further increased to 0.0013 kg/s at 1.2 kg. Fir wood showed a similar trend, with FCR values of 0.0007 kg/s, 0.0010 kg/s, and 0.0012 kg/s for fuel masses of 0.8 kg, 1.0 kg, and 1.2 kg, respectively. Meanwhile, coffee wood produced FCR values of 0.0007 kg/s at 0.8 kg, 0.0009 kg/s at 1.0 kg, and 0.0011 kg/s at 1.2 kg. These results indicate that increasing the fuel mass consistently increased the fuel consumption rate for all three types of wood.

The increase in FCR with increasing fuel mass can be attributed to the greater amount of combustible material available in the combustion chamber. A larger fuel mass provides a greater supply of fuel to sustain the combustion process, resulting in a higher rate of fuel consumption. In addition, differences in the physical and combustion characteristics of each wood type, such as density, moisture content, structure, and volatile matter content, may affect the combustion rate. Pine wood exhibited the highest FCR at each fuel mass compared with fir and coffee wood. This indicates that pine wood was consumed at a faster rate under the operating conditions of the biomass stove. The relatively high FCR of pine wood may be related to its combustion characteristics, which allowed heat to be released at a relatively high rate during the combustion process.

Based on the fuel consumption rate analysis, the highest FCR obtained in this study was 0.0013 kg/s, using 1.2 kg of pine wood. This value represents the highest fuel consumption rate among all tested fuel variations. The result suggests that the combination of pine wood and a fuel mass of 1.2 kg produced the most intensive fuel consumption during the combustion process. Although a higher FCR indicates a faster consumption of fuel, it should not be interpreted solely as better stove performance because fuel consumption must also be considered in relation to the thermal power and thermal efficiency produced. A high fuel consumption rate can provide greater heat input, but excessive fuel consumption may also increase fuel requirements during operation.

The findings are comparable to previous studies. [22], using mountain fir wood as fuel, reported an FCR of 0.0014 kg/s, which was slightly higher than the maximum value obtained in the present study. The difference may be associated with variations in fuel characteristics, combustion chamber conditions, operating parameters, and heat transfer mechanisms. Meanwhile, [23], who investigated a steam-injection biomass stove using mountain fir wood with variations in injected water volume, reported a fuel consumption rate of 0.0012 kg/s. The maximum FCR obtained in the present study was therefore slightly higher than that reported by [23]. Overall, the results demonstrate that increasing fuel mass tends to increase the FCR, while the type of wood fuel also plays an important role in determining the rate of fuel consumption in a steam-injection biomass stove.

Thermal Power

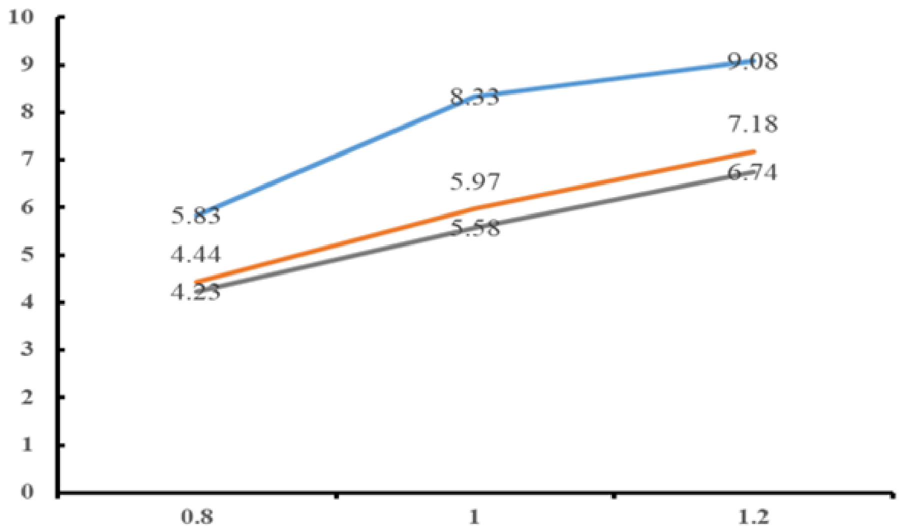

Figure 5. Thermal Power

Figure 2 shows the effect of wood fuel type and fuel mass on the thermal power produced by the steam-injection biomass stove. The results indicate a clear increase in thermal power as the fuel mass increases for all three types of wood fuel. For pine wood, the thermal power increased from 5.83321 kcal/s at a fuel mass of 0.8 kg to 8.33315 kcal/s at 1.0 kg and reached 9.07647 kcal/s at 1.2 kg. Fir wood produced thermal power values of 4.61290 kcal/s, 5.96895 kcal/s, and 7.18381 kcal/s at fuel masses of 0.8 kg, 1.0 kg, and 1.2 kg, respectively. Meanwhile, coffee wood produced thermal power values of 4.23221 kcal/s, 5.34710 kcal/s, and 6.74384 kcal/s at the corresponding fuel masses. This consistent trend indicates that increasing the amount of fuel supplied to the combustion chamber increases the amount of energy released during combustion, thereby increasing the thermal power generated by the stove.

The increase in thermal power can be explained by the relationship between fuel availability and the amount of chemical energy released during combustion. A larger fuel mass provides a greater quantity of combustible material, allowing more energy to be released over the combustion period. As the fuel undergoes combustion, the chemical energy stored in the biomass is converted into heat energy. Part of this heat is then transferred to the water in the injector system, contributing to water evaporation and steam production. Therefore, an increase in fuel mass generally results in a greater heat supply and consequently a higher thermal power output. This relationship is also consistent with the fuel consumption rate results, where an increase in fuel mass was accompanied by an increase in FCR.

For pine wood, increasing the fuel mass from 0.8 kg to 1.0 kg increased the thermal power by approximately 42.85%, while increasing the mass from 1.0 kg to 1.2 kg resulted in a further increase of approximately 8.92%. Overall, the increase from 0.8 kg to 1.2 kg resulted in an increase of approximately 55.63%. These results indicate that the addition of fuel initially produced a substantial increase in thermal power, although the rate of increase became smaller at the highest fuel mass. This may indicate that the combustion process and heat transfer system have operating limitations, so that additional fuel does not always produce a proportional increase in useful thermal output.

A similar pattern was observed for fir wood. The thermal power increased from 4.61290 kcal/s at 0.8 kg to 5.96895 kcal/s at 1.0 kg, representing an increase of approximately 29.39%. At 1.2 kg, the thermal power reached 7.18381 kcal/s, corresponding to an increase of approximately 20.35% compared with the 1.0 kg variation. Overall, the thermal power of fir wood increased by approximately 55.73% from 0.8 kg to

1.2 kg. This demonstrates that increasing the fuel mass can substantially increase the heat output of the stove, although the magnitude of the increase depends on the characteristics of the fuel.

Coffee wood also showed an increasing trend, although its thermal power remained lower than that of pine and fir wood at all fuel masses. The thermal power increased from 4.23221 kcal/s at 0.8 kg to 5.34710 kcal/s at 1.0 kg and reached 6.74384 kcal/s at 1.2 kg. The overall increase from 0.8 kg to 1.2 kg was approximately 59.44%, representing the largest relative increase among the three fuel types. Nevertheless, the absolute thermal power remained lower than that produced by pine and fir wood. This suggests that the quantity of fuel alone does not determine the heat output; the physical and combustion properties of the wood also play an important role.

Among the three fuel types, pine wood consistently produced the highest thermal power at all tested fuel masses, followed by fir wood and coffee wood. At a fuel mass of 0.8 kg, pine wood produced 5.83321 kcal/s, which was higher than fir wood at 4.61290 kcal/s and coffee wood at 4.23221 kcal/s. At 1.0 kg, pine wood also maintained the highest value of 8.33315 kcal/s, compared with 5.96895 kcal/s for fir wood and 5.34710 kcal/s for coffee wood. The same pattern was observed at 1.2 kg, where pine wood produced the maximum thermal power of 9.07647 kcal/s, followed by fir wood at 7.18381 kcal/s and coffee wood at 6.74384 kcal/s.

The higher thermal power produced by pine wood may be related to differences in its physical structure, moisture content, density, and combustion characteristics. Wood with suitable combustion characteristics can release energy more rapidly and maintain a relatively stable combustion process, allowing a greater amount of heat to be transferred to the water and injector system. The high thermal power of pine wood is also consistent with its highest FCR value of 0.0013 kg/s at 1.2 kg. This indicates that pine wood was consumed at the highest rate and simultaneously generated the highest heat output. Therefore, the high thermal power obtained from pine wood was associated with a greater rate of fuel consumption.

However, the highest thermal power should not automatically be interpreted as the best overall performance of the biomass stove. Thermal power describes the rate at which thermal energy is generated, whereas thermal efficiency indicates how effectively the energy contained in the fuel is converted into useful heat. A high thermal power accompanied by a high fuel consumption rate may increase the energy input without necessarily improving energy utilization. This is important because the objective of biomass stove operation is not only to produce a large amount of heat but also to utilize the available fuel energy effectively. Therefore, the thermal power results need to be considered together with the FCR and thermal efficiency results to determine the most appropriate operating condition.

The highest thermal power obtained in this study was 9.07647 kcal/s, using 1.2 kg of pine wood. This result demonstrates that this fuel variation provided the greatest heat output among all tested conditions. The high heat output can be beneficial when rapid heating and high steam production are prioritized. However, the corresponding FCR was also the highest, meaning that this operating condition required a greater rate of fuel consumption. Consequently, the selection of 1.2 kg of pine wood as an operating condition should be adjusted according to the intended application, particularly when the priority is high heating capacity rather than minimum fuel consumption.

For comparison, [22] reported a thermal power of 5.9963 kcal/s using mountain fir wood, which was lower than the maximum value obtained in the present study. Meanwhile, [23] reported a higher thermal power of 32.977 kcal/s using a steam-injection biomass stove with mountain fir wood. These differences may be attributed to variations in fuel characteristics, fuel mass, injected water volume, combustion conditions, stove configuration, and heat transfer mechanisms.

Overall, the results indicate that both fuel type and fuel mass affect the thermal power of the steam-injection biomass stove. Increasing the fuel mass from 0.8 kg to 1.2 kg increased the thermal power for all tested wood types. The highest thermal power of 9.07647 kcal/s was obtained using 1.2 kg of pine wood, making this variation the most suitable when maximum heat output is prioritized. However, the optimal operating condition should also consider fuel consumption rate and thermal efficiency to achieve effective and efficient biomass stove performance.

Thermal Efficiency

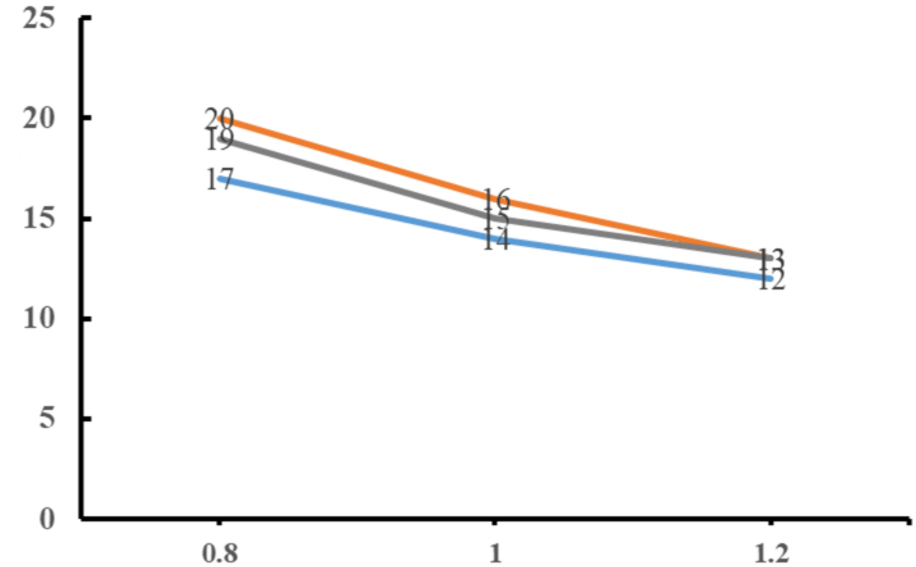

Figure 6. Thermal Efficiency

Figure 3 presents the effect of wood fuel type and fuel mass on the thermal efficiency of the steam-injection biomass stove. The results show that thermal efficiency decreased as the fuel mass increased for all three types of wood fuel. For fir wood, the thermal efficiency (η_t) was 20% at a fuel mass of 0.8 kg, decreased to 16% at 1.0 kg, and further decreased to 13% at 1.2 kg. Coffee wood showed a similar trend, with thermal efficiencies of 19%, 15%, and 13% at fuel masses of 0.8 kg, 1.0 kg, and 1.2 kg, respectively. Meanwhile, pine wood produced thermal efficiencies of 17%, 14%, and 13% at the same fuel masses. These results indicate that the increase in fuel mass did not result in a proportional increase in the useful thermal energy transferred to the water.

The decrease in thermal efficiency with increasing fuel mass can be attributed to the increasing amount of energy supplied to the combustion process. Although a larger fuel mass generates greater thermal energy and increases the thermal power, not all of the energy can be effectively transferred to the water. A portion of the heat may be lost through the stove walls, exhaust gases, radiation, convection, and incomplete heat transfer between the combustion chamber and the water. As the amount of fuel increases, these heat losses can become more significant, resulting in a lower proportion of the total fuel energy being converted into useful thermal energy. Therefore, a higher fuel mass may increase heat production but does not necessarily improve the efficiency of energy utilization.

The results also show that fir wood produced the highest thermal efficiency at the lowest fuel mass. The efficiency of 20% at 0.8 kg of fir wood was the highest value among all tested variations. This was followed by coffee wood at 19% and pine wood at 17% under the same fuel mass. The higher efficiency of fir wood may be related to its combustion characteristics, which allowed a relatively effective conversion of fuel energy into useful heat at the lower fuel mass. At higher fuel masses, however, the efficiency of all fuel types decreased and approached a similar value of 13% at 1.2 kg. This suggests that increasing the fuel mass may reduce the effectiveness of heat utilization regardless of the type of wood used.

The relationship between thermal efficiency and thermal power is also important to consider. Pine wood at 1.2 kg produced the highest thermal power of 9.07647 kcal/s, but its thermal efficiency was only 13%. In contrast, fir wood at 0.8 kg produced the highest thermal efficiency of 20%, despite having a lower thermal power. This finding confirms that high thermal power does not necessarily indicate high thermal efficiency. Thermal power represents the rate of heat generation, whereas thermal efficiency reflects the proportion of fuel energy that is successfully converted into useful thermal energy. Therefore, both parameters should be evaluated together when determining the overall performance of the biomass stove.

Based on the thermal efficiency analysis, the highest efficiency obtained in this study was 20%, using 0.8 kg of fir wood. This result indicates that the lower fuel mass provided a more favorable balance between heat generation and heat utilization. The relatively lower amount of fuel may have reduced excessive heat losses while still providing sufficient energy to heat the water and generate steam. Therefore, when fuel efficiency is prioritized rather than maximum thermal output, the use of 0.8 kg of fir wood provides a more favorable operating condition.

The thermal efficiency obtained in this study is comparable to the results reported by Topan Limbongallo (2024), who obtained a thermal efficiency of 21% using mountain fir wood. The value obtained in the present study was slightly lower, with a difference of approximately 1 percentage point. Meanwhile, [23], who investigated a steam-injection biomass stove using mountain fir wood with variations in injected water volume, reported a substantially higher thermal efficiency of 51%. The differences between these results may be influenced by variations in fuel properties, fuel mass, water volume, combustion conditions, stove design, and heat transfer characteristics.

Overall, the results demonstrate that increasing fuel mass is not always beneficial in terms of thermal efficiency. The optimum fuel condition depends on the performance parameter being prioritized. A fuel mass of 1.2 kg of pine wood was favorable for achieving the highest thermal power, whereas 0.8 kg of fir wood provided the highest thermal efficiency of 20%. These findings indicate that optimizing the operation of the steam-injection biomass stove requires consideration of fuel type and fuel mass simultaneously to achieve an appropriate balance between heat output and energy utilization.

CONCLUSION

Based on the results of the study, several conclusions can be drawn regarding the performance of the steam-injection biomass stove using different types and masses of wood fuel. The highest fuel consumption rate (FCR) was obtained at 0.0013 kg/s, using 1.2 kg of pine wood. This result indicates that the use of a higher fuel mass, particularly pine wood, resulted in a higher combustion rate and greater fuel consumption during the combustion process.

The highest thermal power was obtained at 9.07647 kcal/s, also using 1.2 kg of pine wood. This result demonstrates that pine wood at a fuel mass of 1.2 kg was able to produce the greatest heat output among the tested fuel variations. The higher thermal power is associated with the greater amount of fuel available for combustion, which provides a larger energy supply to the heating system.

In contrast, the highest thermal efficiency was obtained at 20%, using 0.8 kg of fir wood. This finding indicates that the highest heat output does not necessarily correspond to the highest thermal efficiency. The 0.8 kg fir wood variation was able to utilize the supplied combustion energy more effectively for the heating process, resulting in the highest proportion of useful thermal energy compared with the other fuel variations. Overall, the results indicate that the optimum fuel condition depends on the performance parameter considered, with 1.2 kg of pine wood providing the highest fuel consumption rate and thermal power, while 0.8 kg of fir wood providing the highest thermal efficiency.

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