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Effect of Washing and Torrefaction Pretreatments on Fuel Properties of Rice Husk-Based Bio-Pellets

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Abstract

Rice husk is an abundant agricultural waste in Indonesia and has potential as a biomass fuel for co-firing in steam power plant boilers. This study investigated the effects of washing and torrefaction pretreatments on the fuel properties of rice husk-based bio-pellets to reduce ash content and improve calorific value. Rice husk was washed using water at 70 ± 5°C under two conditions, with stirring and without stirring, while untreated rice husk was used as a control. Torrefaction was conducted at 260°C, and the treated biomass was pelletized using tapioca starch as a binder at 30% of the raw material weight. The results showed that the lowest ash content (26.362%) was obtained from bio-pellets produced from rice husk washed without stirring, indicating that washing was effective in reducing ash content. The highest calorific value (4456.4 kcal/kg) was recorded in bio-pellets produced from untreated rice husk, while the highest combustion rate (0.504 g/min) was observed in the washed and torrefied samples. The findings indicate a trade-off between ash reduction and energy performance, depending on the pretreatment combination. However, all samples showed relatively high ash content (26%–36%), which may limit their direct suitability for co-firing without further ash reduction treatment.

Keywords:
Ash content, bio-pellets, calorific value, rice husk, torrefaction

1 Introduction

Co-firing refers to the simultaneous combustion of two different types of feedstocks. This approach is considered a potential strategy for reducing pollution, particularly in Indonesia. Energy plays a crucial role in supporting economic activities and strengthening national energy security. One effort to increase the share of renewable energy is the implementation of biomass co-firing with coal in existing coal-fired power plants [1]. Biomass is generally considered a potentially carbon-neutral energy source under sustainable management practices, since CO_2 released during combustion can be offset by carbon uptake during biomass growth. However, CO_2 emissions still occur during combustion as well as in processes such as drying, transportation, and pretreatment. In addition, biomass typically contains lower sulfur content than coal [2]. Based on available data, rice husk production in Aceh Province reached 326,927.9 tons in 2021.

Rice husk contains a high ash content due to its high silica concentration and generally has a relatively low calorific value. Therefore, pretreatment is required to enhance its calorific value and reduce ash content. In this study, the pretreatment processes applied were washing using heated well water and torrefaction. Washing rice husk with water is considered an effective method for removing inorganic compounds contained in ash. Previous findings showed that washing rice husk with hot water at 50°C for 2 hours was able to reduce ash content by 23.5% [3].

The calorific value of biomass, particularly rice husk, remains relatively low. Rice husk has a bulk density of approximately 125 kg/m³, with a calorific value of 3,300 kcal per kilogram of rice husk [4]. One method commonly applied to increase the calorific value is torrefaction. Torrefaction is a thermochemical process conducted at temperatures of 200–300°C under an inert atmosphere, during which biomass loses moisture, the oxygen-to-carbon (O/C) ratio decreases, and the energy content increases [5].

The advantages of torrefaction include its operation at relatively low temperatures and pressures, as well as its high energy conversion efficiency, which can reach approximately 90%. Mild torrefaction treatment of dried rice husk at 230°C and 260°C for 30 minutes has been reported as an optimal condition for improving hydrophobicity, calorific value, and grindability, while minimizing solid and energy yield losses. Under these conditions, the Higher Heating Value (HHV) reached 17.53 MJ/kg, equivalent to 4,186.96 kcal/kg, with an ash content of 27.64% [6].

In relation to these characteristics, the low density of biomass represents a significant limitation for its utilization as a solid fuel. One densification process that can be applied to improve biomass density is pelletization, in which biomass is compacted into pellet form. This process can also increase the calorific value per unit volume, enabling bio-pellets to be directly utilized as solid fuels with properties that are more comparable to coal [7]. According to Nani Siska Putri Khan et al. (2026), increasing torrefaction temperature can improve biomass fuel quality by reducing moisture content and volatile matter while increasing fixed carbon, although it may also reduce solid yield [8].

The objective of this study was to evaluate the combustion characteristics of bio-pellet products prepared using three different treatment methods, including (i) torrefied rice husk without pre-washing treatment, hereafter referred to as original rice husk; (ii) rice husk washed without stirring, followed by torrefaction; (iii) rice husk washed with stirring, followed by torrefaction. Unlike purely descriptive studies, this work focuses on comparing how different washing conditions influence ash reduction efficiency and whether such pretreatment affects calorific value and combustion behavior after torrefaction. The expected contribution of the bio-pellet products prepared using these three methods is to provide a comparative assessment of their physical, mechanical and combustion properties. Furthermore, the resulting bio-pellets are expected to demonstrate potential for further development toward commercial-scale solid fuel products.

2 Research methods

2.1 Materials and equipment

The rice husk feedstock used in this study was obtained from a rice mill located in Gampong Paya Dua, Banda Baro District, Aceh Utara, Aceh, Indonesia. The rice husk was collected in a dry condition. A random sampling method was applied during feedstock collection to ensure representativeness of the raw material. The experimental work was conducted at the Mechanical Engineering Laboratory of Universitas Malikussaleh, the Mechanical Engineering Laboratory of Politeknik Negeri Lhokseumawe, and the Laboratory of the Faculty of Agriculture, Universitas Malikussaleh.

The materials used in this study included rice husk, tap water, tapioca starch, and a 12 kg Liquefied Petroleum Gas (LPG) cylinder used as fuel. The equipment used in this study consisted of a pyrolyzer, a flat roller die pelletizing machine, drying containers, mixing containers, a 20-mesh sieve, an analytical balance, an oven, a desiccator, a bomb calorimeter, porcelain crucibles, a stopwatch, a combustion rate testing apparatus, a grinder, and a camera. All characterization tests and measurements were conducted in triplicate (n = 3), and the results reported in all tables represent mean values ± standard deviation (mean ± SD).

2.2 Washing pretreatment

This study involved three treatment conditions: untreated rice husk, rice husk washed without stirring, and rice husk washed with stirring. The untreated rice husk was not subjected to any washing process, whereas the remaining samples underwent a washing pretreatment.

For the rice husk washed without stirring, the washing process was carried out using a raw material-to-water ratio of 1:15. After the initial washing step, the rice husk was drained using a plastic sieve. A total of 15 kg of water was heated to 70°C ± 5°C using a 12 kg LPG cylinder. The drained rice husk was then immersed in the heated water and soaked for 15 minutes.

For the rice husk washed with stirring, the washing process was also conducted at a raw material-to-water ratio of 1:15. After washing, the rice husk was drained using a plastic sieve. Subsequently, 15 kg of well water was heated to 70°C ± 5°C using a 12 kg LPG cylinder. The drained rice husk was then added to the heated water and stirred for 15 minutes using a drilling machine operated at the lowest rotational speed. The washing water used in this study was well water. During washing, a visible difference in water color was observed. The water from the 70°C ± 5°C washing process appeared darker compared to normal washing water, indicating a higher level of extracted impurities. This is because room-temperature water primarily removes surface contaminants such as soil, dust, and mud. Previous studies by Zhang et al. (2015) reported that hot-water washing is an effective pretreatment method for removing inorganic components in rice husk, including potassium (95%), chlorine (54%), sulfur (37%), and phosphorus (53%).

2.3 Drying

The drying process was conducted using a solar thermal drying chamber. This method was applied to minimize the contamination of the raw material by excessive ash, dust, or other impurities during sun-drying. The drying process was carried out for four days under clear weather conditions. The raw material was weighed before and after drying to determine its moisture content.

2.4 Torrefaction

The torrefaction process was conducted under three experimental conditions: untreated rice husk, washed rice husk without stirring, and washed rice husk with stirring. For each run, 1 kg of dried rice husk was weighed and loaded into the reactor tube. At the beginning and end of each experiment, the gas cylinder was weighed using a digital balance to determine fuel consumption during the process. The cooling water pump was then activated to ensure continuous water circulation through the condenser system. All valves were ensured to be in a closed position before heating. The torrefaction process was conducted at a single temperature range of 260°C–280°C. Temperature and pressure data were recorded at 1minute intervals using a thermometer and pressure gauge.

During heating, biomass underwent thermal decomposition according to temperature stages. The resulting vapors passed through a connecting pipe into a separator. In the separator, heavier compounds such as water and tar were condensed and collected at the bottom. Lighter vapors proceeded to the condenser, where phase change from vapor to liquid occurred. The condensed liquid was collected in a second separator. Non-condensable gases were directed to a gas storage unit.

Thus, the torrefaction process produced three products: biochar (solid residue from reactor decomposition), bio-oil (condensed liquid fraction), and non-condensable gas. The process was continued until the target temperature of 260°C was reached and maintained for 60 minutes. Temperature stability was controlled by adjusting valve openings in the reactor system to regulate pressure and gas flow.

Each experimental condition was repeated three times to obtain average torrefaction yields. If the biochar produced in the first run was less than 500 g, the remaining required amount was supplemented using biochar from the second run of the same sample condition. This procedure was applied consistently for all sample variations.

2.5 Bio-pellet production

The bio-pellets were produced using a flat roller die-type bio-pellet machine, as shown in Fig. 1.

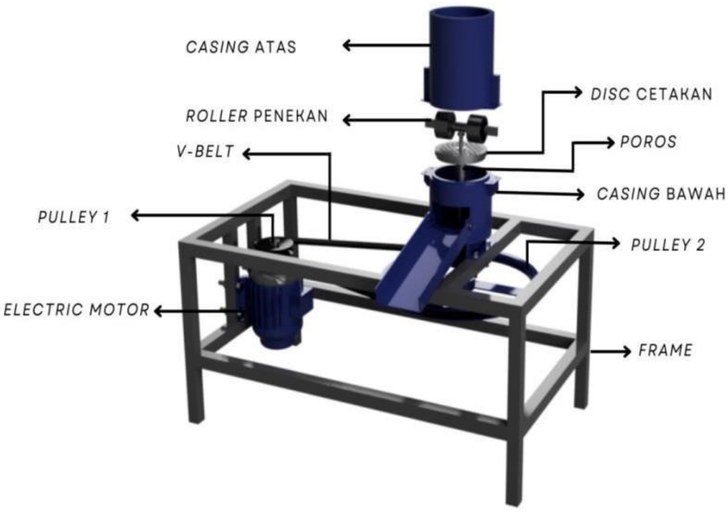

Fig. 1. Flat roller die-type pellet machine

A total of 500 g of biochar was weighed for each pelletization process. The ratio of binder was fixed at 30% of the raw material weight. Therefore, the binder was prepared proportionally based on 500 g of biochar, ensuring consistent composition across all sample variations.

Tapioca starch (30% of biochar weight) was mixed with 500 g of water and heated until a slightly viscous binder was formed. The biochar was then crushed using a crusher machine and sieved using a 20-mesh sieve to obtain a uniform particle size.

The biochar and binder were mixed thoroughly until a homogeneous mixture was obtained. The mixture was then fed into the vertical pelletizing machine with a mold diameter of 120 mm, a hole size of 8 mm, and a thickness of 17 mm. The produced bio-pellets were dried in an oven at 105°C for 6 hours.

2.6 Characterization and testing

The physical and combustion properties of the bio-pellets were evaluated, including proximate analysis (ash content, moisture content, volatile matter, fixed carbon), calorific value, and combustion rate. All measurements were performed in triplicate (n = 3). The values reported in tables represent the mean ± standard deviation. Several Indonesian National Standards (SNI) were referenced in this study for different purposes. SNI 8951:2020 was used as the primary standard for evaluating bio-pellet quality. Meanwhile, SNI 06-3730, SNI 01-1506, and SNI 01-6235 were used as supporting standards for specific analytical methods and reference parameters relevant to the characterization of rice husk bio-pellets.

1. Ash content
   Biomass contains ash, which refers to the inorganic solid residue remaining after combustion. The dominant solid residues formed during combustion may include silica, aluminum, iron, and calcium. Other inorganic compounds, such as magnesium, titanium, sodium, and potassium, may also be present, although in smaller quantities. In accordance with the SNI 06-3730 standard [9], ash content can be determined using the formula presented in Eq. (1).

$$Ash\ content\ (\%) = \frac{W_1}{W_2} \times 100 \tag{1}$$

where W_1 is the mass of ash residue after combustion (g), and W_2 is the initial dry sample mass (g).

2. Moisture content
Excessive moisture content in solid fuels, including coal and biomass-based fuels, can reduce the calorific value during combustion [10]. Moisture content also affects the ignition rate. A higher moisture content may prolong the initial ignition time because the biomass must first release and evaporate the water contained in the material before combustion can occur. The equation used to calculate moisture content, based on the SNI 01-1506 standard [11], is shown in Eq. (2).

$$Moisture\ content\ (\%) = \frac{W_i - W_f}{W_i} \times 100 \quad (2)$$

where W_i is the initial sample mass (g), and W_f is the final mass after drying (g).

3. Volatile matter
Volatile matter refers to the fraction of biomass that is released as vapor or gas during thermal decomposition. This component affects combustion completeness and the flame characteristics produced during combustion. The volatile matter content was calculated based on the SNI 06-3730 standard, as presented in sing Eq. (3).

$$Volatile\ matter\ (\%) = \frac{W_a - W_b}{W_a} \times 100 \quad (3)$$

where W_a is the mass of the dry sample before the volatile matter test (g), and W_b = mass after heating at the volatile matter condition (g).

4. Fixed carbon content
Fixed carbon refers to the carbon fraction retained in biomass in solid form after the release of moisture and volatile matter. The fixed carbon content contributes to heat generation during combustion; therefore, a higher fixed carbon content generally indicates a greater potential for sustained heat release. The fixed carbon content was calculated based on the SNI 06-3730 standard, as shown in Eq. (4).

$$Fixed\ carbon\ (\%) = 100 - (VM + A + M) \quad (4)$$

where VM is volatile matter (%), A is ash content (%), and M is moisture content (%).

5. Calorific value
The calorific value of a fuel is defined as the maximum amount of heat energy released by a fuel through complete combustion per unit mass or volume. This analysis was conducted to determine the amount of thermal energy that the fuel can release during the combustion process [12]. The calorific value test was carried out in accordance with the SNI 01-6235-2000 standard [13]. The calorific value was measured using an Automatic Calorimeter IKA-C 2000.

6. Combustion rate
The combustion rate test was conducted to determine the burning rate of biomass pellets for each specimen. The test was performed manually by burning the biomass pellets on an iron plate. First, each bio-pellet specimen was weighed to determine its initial mass. After combustion, the remaining mass was measured to obtain the final mass of each specimen. The specimen was burned until it turned into ash or until the temperature of the burned bio-pellet decreased to ambient temperature. Temperature measurement was conducted using a thermocouple, while the combustion duration was recorded using a stopwatch [14]. The combustion rate was calculated using Eq. (5).

$$CR = \frac{M_b}{t} \quad (5)$$

Where CR is the combustion rate (g/min), M_b is the mass of the burned pellet (g), t is the combustion time (min).

The mass of the burned pellet was calculated using Eq. (6), where M_i is the initial mass of the pellet (g), M_r is the remaining mass after combustion (g).

$$M_b = M_i - M_r \quad (6)$$

The combustion rate testing apparatus is presented in Fig. 2. The combustion rate testing procedure was adapted from reference [15], with modifications in terms of material type and fuel quantity. The experimental procedure was conducted as follows:

a. The combustion rate testing apparatus was prepared, including the installation of a type-K thermocouple and its control system, fuel furnace, burner, fuel source (ethanol), aluminum plate, and wire mesh plate.
b. A total of 5 g of ethanol was introduced into the burner as the ignition fuel for the initial combustion process.
c. The digital balance was then set to zero using the tare function.
d. A 50 g bio-pellet sample was weighed for each combustion test.
e. The ambient temperature and initial mass of the bio-pellet sample were recorded before combustion.
f. The ignition fuel was ignited, and the temperature, mass reduction of the bio-pellet, and combustion time were recorded during the burning process.
g. The combustion time was measured using a stopwatch, while the temperature was measured using a type-K thermocouple. The mass of the bio-pellet was measured using a digital balance.
h. Data were recorded at 1-minute intervals, starting from the initial ignition of the fuel.
i. The measured parameters included combustion time, temperature, and bio-pellet mass.
j. The combustion process was considered complete when the entire bio-pellet sample had been converted into ash, and the temperature had decreased to ambient temperature.
k. The combustion rate was calculated by dividing the mass of burned bio-pellet by the total combustion time.

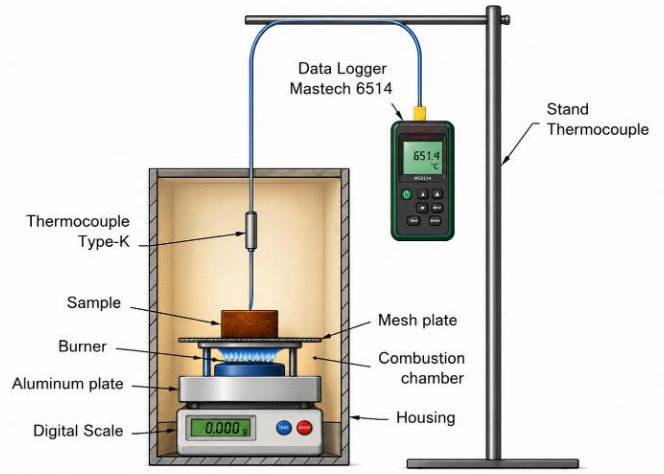

Fig. 2. Schematic diagram of the combustion rate testing apparatus

3 Results and discussion

3.1 Experimental results of torrefaction at 260°C

The following section presents the temperature profiles of the torrefaction process conducted at 260°C with a residence time of 60 minutes for the three rice husk-based experimental variables.

1. Temperature increase profiles during torrefaction

The temperature increase profiles during the torrefaction of rice husk under different pretreatment conditions are presented in Fig. 3.

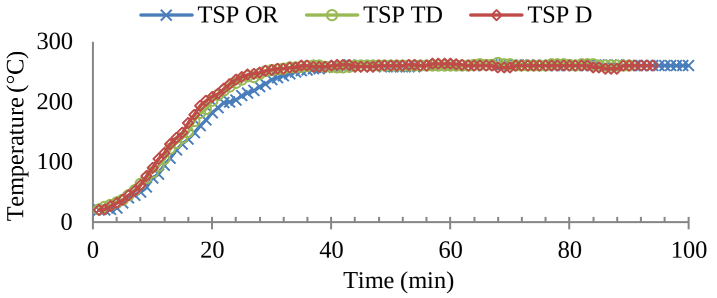

Fig. 3. Temperature increase profiles during torrefaction of rice husk under different pretreatment conditions: untreated rice husk, rice husk washed at 70°C ± 5°C with stirring, and rice husk washed at 70°C ± 5°C without stirring

Fig. 3 shows the temperature increase profiles during the torrefaction process of rice husk under three different pretreatment conditions. Overall, all samples showed a gradual increase in temperature until reaching the target torrefaction temperature of 260°C, followed by a holding period of 60 minutes. However, differences in heating duration were observed among the samples. The untreated rice husk required the longest average processing time, namely 93.67 minutes, while the rice husk washed with stirring and without stirring required average processing times of 87.3 minutes and 82 minutes, respectively.

The variation in heating profiles was mainly influenced by operational stability during the torrefaction process. In several trials, longer heating durations were associated with unstable temperature control, incomplete opening of the LPG regulator valve, condenser water overflow into the burner area, and leakage in the condenser coil pipe. The condenser water overflow affected the heating stability because the apparatus configuration allowed water to enter the burner area [16]. These conditions caused fluctuations in the heating process and prolonged the time required for the reactor to reach a stable operating temperature. In contrast, trials with more stable temperature control showed faster heating rates and more consistent torrefaction performance.

Thus, the combined temperature profiles indicate that both pretreatment conditions and operational factors affected the torrefaction process. Stable temperature control, proper LPG flow regulation, and controlled condenser water circulation are important factors in achieving consistent heating performance and improving fuel-use efficiency during torrefaction.

2. Distribution of torrefaction products at 260°C

The distribution of torrefaction products obtained at a temperature of 260°C with a residence time of 60 minutes for the three rice husk-based variables is presented in Table 1.

Table 1. Torrefaction product distribution

Sample	Biochar (wt.%)	Bio-oil (wt.%)	Non-condensable Gas (wt.%)
TSP OR	47.5	30.33	22.17
TSP TD	56.17	23.17	20.67
TSP D	52.0	28.67	19.33

Table 1. shows the distribution of products generated from the rice husk torrefaction process. The dominant product obtained from the process was biochar. The highest biochar yield was observed in the rice husk sample washed without stirring, with a mass of 561.7 g (56.17 wt.%). The highest bio-oil yield was obtained from the rice husk sample washed with stirring, reaching 286.7 g. Meanwhile, the highest amount of non-condensable gas was produced from the untreated rice husk sample, with a mass of 221.7 g (22.17 wt.%).

Based on the product distribution, it can be concluded that the torrefaction process produced a higher proportion of biochar compared to bio-oil and non-condensable gas. This result is consistent with findings reported [17], which explains that torrefaction is a thermochemical conversion process conducted at a relatively low temperature compared with other thermochemical conversion methods. This is also related to the explanation in [18], which states that temperature plays an important role in torrefaction because it determines the extent of thermal degradation in biomass. As the process temperature increases, the mass of biomass tends to decrease.

The bio-oil yield obtained in this experiment was relatively low. This condition can be attributed to the relatively low operating temperature of 260°C. At this temperature, some volatile matter contained in the raw material may not have been completely decomposed, thereby limiting the formation of liquid products during the torrefaction process.

3.2 Bio-pellet characteristics

3.2.1 Size distribution

The bio-pellet products produced using the pelletizing machine had a uniform diameter of 8 mm, while their lengths varied. The resulting bio-pellet products are shown in Fig. 4. The classification of bio-pellet size groups is presented in the size distribution diagram shown in Fig. 5.

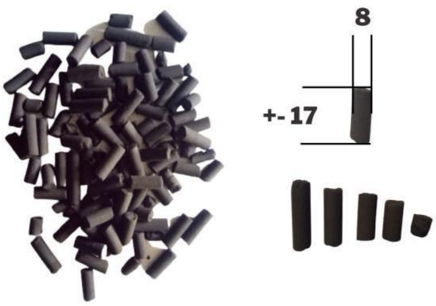

Fig. 4. Bio-pellet products

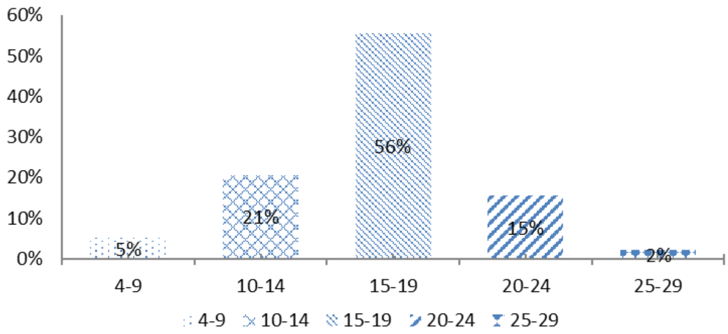

Fig. 5. Size distribution diagram

From the 97 measured samples, the most dominant pellet length produced by the bio-pellet machine was in the range of 15–19 mm, accounting for 56% of the total samples. In contrast, the least frequently produced size range was 25–29 mm, representing only 2% of the samples. This result is consistent with the dimensions of the mold disc used in the bio-pellet machine, which had a disc diameter of 120 mm, a mold hole diameter of 8 mm, and a mold thickness of 17 mm.

The densification process converted rice husk, which initially had a flat and irregular morphology, into bio-pellets. This transformation provides several advantages, particularly in terms of transportation and distribution to end users, such as coal-fired power plants and other potential consumers. This finding is in accordance with the study reported in [19], which stated that biomass compaction or densification can improve biomass quality while also reducing transportation, handling, and storage costs.

Based on the bio-pellet molding process, the use of a higher mesh number resulted in a greater requirement for binder addition and produced bio-pellets with higher density. Conversely, the use of a lower mesh number required less binder; however, the resulting bio-pellets exhibited lower density.

3.2.2 Proximate analysis and calorific value

The standard used for testing the pellet products was SNI 8951:2020 for utility-grade applications. The results of the proximate analysis are presented in Table 2. Untreated rice husk bio-pellets satisfied several key parameters specified in SNI 8951:2020, although not all quality criteria were fully met.

Table 2. Results of proximate analysis and calorific value testing of bio-pellets

Sample	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)
TSP OR	2.866	30.994	35.361	30.779
TSP TD	4.352	26.362	46.093	23.193
TSP D	2.857	36.027	34.259	26.857

The highest moisture content was observed in the TSP TD sample, with a value of 4.352%, whereas the lowest moisture content was found in the TSP D sample, with a value of 2.857%. This difference was attributed to non-uniform drying during the oven-drying process, which may have occurred due to excessive sample stacking during drying. In addition, binder addition may also increase the moisture content, while the water added during bio-pellet molding can further contribute to higher moisture levels.

This finding is consistent with the statement in [21], which explains that the water added during the mixing process and additional materials affected the increase in bio-pellet moisture content. In this study, the moisture content of the bio-pellets met the requirements and complied with the SNI 01-1506 standard [11].

The lowest ash content was observed in the TSP TD sample, with a value of approximately 26%. The TSP TD sample was produced through washing pretreatment using water heated to 70°C ± 5°C without stirring. The ash content decreased by 4.63% compared with the untreated original rice husk sample and by approximately 10% compared with the rice husk sample washed with stirring. These results indicate that hot-water washing without stirring has the potential to remove inorganic compounds from rice husk. This finding is consistent with the study reported in [3], which showed that washing rice husk with hot water at 50°C for 2 hours reduced ash content by 23.5%. However, the washing treatment applied in this study produced different results, which may be attributed to differences in the chemical characteristics of the well water obtained from different locations.

Another factor contributing to the high ash content is the presence of mineral compounds, particularly because water was added during the bio-pellet production process. Water addition was required because the biochar obtained from the torrefaction process was extremely dry, making it difficult to mold into bio-pellets. According to [22], excessively high ash content can be caused by minerals that remain in the material and are not completely combusted. Therefore, the high ash content observed in this study may be associated with the mineral content introduced or retained during water addition in the bio-pellet production process.

The relatively high ash content was also influenced by the binder percentage, as this study used 30% binder in the bio-pellet formulation. As reported in [23], the addition of binder materials to pellets can increase the moisture content. In addition, binder addition may also contribute to an increase in the ash content of bio-pellets.

Calorific value is a key parameter used to evaluate fuel quality. A higher calorific value indicates a greater amount of energy released during combustion and, therefore, reflects better fuel performance. Accordingly, calorific value is commonly used as a reference indicator for assessing the quality of solid fuels. In this study, calorific value testing was conducted in accordance with the SNI 01-6235 standard. Untreated rice husk bio-pellets satisfied several key parameters specified in SNI 8951:2020, although not all quality criteria were fully met. The results indicate that torrefaction pretreatment increased the calorific value of rice husk-based bio-pellets. The highest calorific value was obtained from the original rice husk bio-pellet sample, with a value of 4456.4 kcal/kg. According to [4], untreated rice husk without torrefaction has a calorific value of approximately 3300 kcal/kg. This comparison demonstrates that the torrefaction process enhanced the calorific value of rice husk across all bio-pellet samples.

This finding is consistent with the statement in [24], which explains that torrefied rice husk exhibits similar behavior to other types of biomass, in which atomic carbon content and calorific value increase with higher torrefaction temperature.

In the samples subjected to washing pretreatment, lower calorific values were obtained for both stirred and non-stirred washed rice husk bio-pellets, with values of 3925.2 kcal/kg and 3890.6 kcal/kg, respectively. The relatively low calorific value was attributed to the higher moisture content of 4.352% and volatile matter content of 46.184%. This result is consistent with the findings reported in [25], which stated that a low calorific value may be caused by high ash content, moisture content, and volatile matter contained in bio-pellets.

When compared with the proximate analysis results, the fixed carbon content showed a positive correlation with calorific value and an inverse relationship with ash content. In other words, a higher fixed carbon content tends to increase the calorific value, whereas a higher ash content tends to reduce the calorific value produced by the bio-pellets**.** This trend is in agreement with the findings of Nani Siska Putri Khan et al. (2026), who reported that higher torrefaction temperatures led to a decrease in moisture content and volatile matter, accompanied by an increase in fixed carbon and ash content, thereby improving the energy density and thermal stability of the pellets [8].

3.2.3 Combustion rate

The combustion rate of bio-pellets refers to the rate at which the bio-pellets are completely burned and converted into ash. Therefore, a higher combustion rate indicates that the bio-pellets burn more rapidly and are converted into ash in a shorter period of time. The combustion test is shown in Fig. 6

Fig. 6. Combustion Rate (a) Bio-pellets during combustion (b) Bio-pellets after combustion

The table (Table 3) shows that the slowest combustion rate was obtained from the TSP OR sample, with a value of 0.337 g/min. In contrast, the fastest combustion rate was observed in the TSP TD sample, with a value of 0.504 g/min. The calorific value also influenced the combustion behavior, where a higher calorific value tended to produce a longer combustion duration. The relationship between temperature and combustion time is presented in Fig. 7.

Table 3. Results of combustion rate testing

Sample	Burned biopellet mass (g)	Time (min)	Combustion rate (g/min)
TSP OR	33.32	99	0.337
TSP TD	35.79	71	0.504
TSP D	30.83	74	0.417

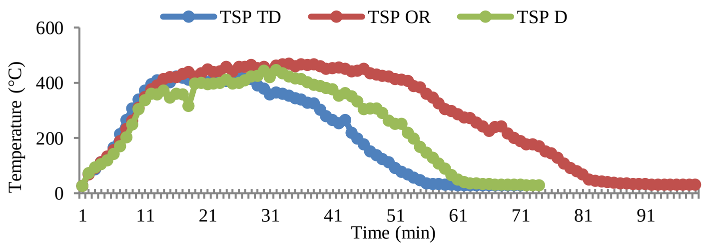

Fig. 7. Relationship between temperature and combustion time

Based on Fig. 7, the highest combustion temperature was observed in the TSP OR sample, reaching 470°C, with the longest ignition duration of 99 minutes. This result was influenced by the calorific value of the bio-pellet, where a higher calorific value tends to produce a higher combustion temperature and a longer burning duration. This finding is consistent with the study reported in [25], which stated that an increase in calorific value results in a slower combustion rate.

The lowest peak temperature was observed in the TSP TD sample, with a temperature of 424.7°C and a total combustion time of 71 minutes. This condition was influenced by the high volatile matter content in the TSP TD sample, which reached 46.18%. The high volatile matter content promoted faster ignition and combustion of the rice husk bio-pellets. A similar result was reported in [25], which found that the fastest combustion rate of bio-briquettes occurred in the composition containing 50% rice husk and 50% wood charcoal. This behavior was attributed to the volatile matter content, where a higher volatile matter content increases the combustibility of bio-briquettes, resulting in a faster combustion process. The mass reduction profile of the bio-pellets is presented in Fig. 8.

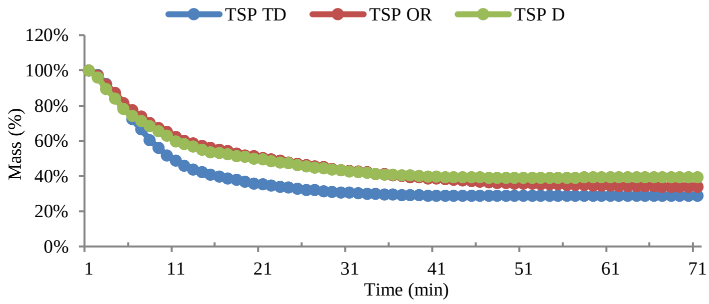

Fig. 8. Relationship between mass and combustion time

The results presented above indicate that the TSP D sample exhibited the highest combustion residue, with a residual mass percentage of 39% (19.9 g) after 74 minutes of combustion. The TSP TD sample showed a residual mass of 29% (14.42 g), although the total combustion time for this sample was only 71 minutes. In contrast, the OR sample produced a combustion residue of 34% (17.17 g) and exhibited the longest combustion duration, reaching 99 minutes, with a maximum temperature of 470.02°C.

A significant reduction in sample mass was observed within the time interval of 1–30 minutes. This mass loss can be attributed to the volatile matter content of the bio-pellets. As shown in Fig. 8, the greatest mass reduction occurred in the TSP TD sample, which had a volatile matter content of 46.09%. The differences in mass loss and combustion duration have a strong relationship with the calorific value and volatile matter content of the bio-pellets. This finding is consistent with the statement reported in [25], which indicated that a higher calorific value is associated with a slower combustion rate. In contrast, a higher volatile matter content increases the ease of ignition and accelerates the combustion process. A similar combustion behavior was reported by Nani Siska Putri Khan et al. (2026), who found that pellets torrefied at higher temperatures exhibited a faster temperature rise and a more gradual mass loss, indicating better combustion efficiency and thermal endurance [8].

These results are also consistent with the proximate analysis, which showed that the highest fixed carbon content and calorific value were obtained in the TSP OR sample. This condition resulted in the longest burning duration for the TSP OR sample. Meanwhile, the highest volatile matter content was observed in the TSP TD sample, which consequently led to the greatest and most rapid mass reduction during combustion.

4 Conclusions

This research demonstrated that washing and torrefaction pretreatments significantly influenced the fuel properties of rice husk-based bio-pellets. Among the washing methods, non-stirred hot-water washing was found to be the most effective in reducing ash content, indicating strong potential for minimizing ash-related operational issues such as slagging, fouling, and excessive residue during combustion. In contrast, untreated rice husk bio-pellets showed superior overall energy-related performance, particularly in terms of fuel characteristics and combustion behavior. These findings reveal an important trade-off between ash reduction and energy performance. Therefore, the selection of a pretreatment method should be based on the intended application, balancing the need for lower ash content with the requirement for higher energy performance and combustion efficiency.

For practical application, further optimization of pretreatment and pelletization parameters is needed to improve overall bio-pellet quality. Future studies should investigate the effects of washing duration, water type, biomass-to-water ratio, binder concentration, and torrefaction temperature to achieve an optimal balance between ash reduction and energy performance.

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