

Torrefaction of rice husk as preparation of coal-biomass co-firing and its propensity on ash deposition

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Abstract

The most extensive use of coal in Indonesia is for electricity generation. Due to increasing concerns about climate change and the need to reduce emissions caused by burning coal, biomass-based fuels are becoming more competitive. The biomass carbonization process, or torrefaction, to produce solid fuel has been introduced elsewhere. This research uses sub-bituminous coal and rice husks, considering Indonesia's large potential for both. The primary objective of this research was to determine the optimal temperature and residence time for the rice husk torrefaction process, intending to reduce the alkali oxide content that led to ash deposition. This was necessary due to the limited information available, particularly for local rice husks from Indonesia. We carried out the rice husk torrefaction at 300, 350, and 400°C temperatures for 30, 60, and 90 minutes. The results show that a temperature of 350°C and a residence time of 60 minutes were the optimal conditions. In these conditions, the potassium and sodium oxides decreased, and the calorific value increased. To get a coal-rice husk blending with a calorific value greater than 5,000 cal/g (ADB), the proportion of coal to rice husk should be 90 and 10%, respectively. The rice husk torrefaction process did not have much influence on the occurrence of ash deposition. However, the torrefaction process increased the calorific value, reduced transportation costs due to the lower moisture content, and improved grindability so that it was easy to blend with coal.

Keywords:

torrefaction; temperature; residence time; alkali; ash deposition

1. Introduction

The need for energy, especially electricity, in Indonesia increases yearly. Human life, population growth, evolving lifestyles, and the proliferation of industries all contribute to energy problems. In 2022, electricity production from coal-fired power plants (CFPPs) was around 71% of the total production (Suharyati et al., 2023). Coal is the focus, as it is among the primary sources of carbon emissions that can accelerate the rate of temperature rise on Earth. Coal is responsible for over 40% of CO₂ emissions per year, making it essential to make efforts to cut global emissions by 45% by 2030 and none by the middle of the century. At the 2023 United Nations Climate Conference (COP 28) in Dubai, United Arab Emirates, the use of coal should gradually reduce in a fair, orderly, and equitable manner to achieve zero emissions by, before, or around 2050. There are also several other options, such as increasing renewable energy capacity up to three times by 2030 and develop-

ing technology to capture CO₂ emissions so they do not pollute the atmosphere.

Some strategic steps are needed to optimize the use of the produced coal to anticipate various potential decreases in income from coal mining due to reduced coal use. Currently, Indonesia's industry uses coal, aside from CFPP, at a rate of around 20%. Therefore, the industry continues to require coal for its production operations. An alternate method of reducing coal use is co-firing coal with biomass, which involves substituting some coal with biomass while monitoring the fuel's quality to meet requirements. This program not only supports the addition of renewable energy to the country's energy mix, but it also has a positive effect on the development of a thriving circular economy or people's economy by creating an electricity ecosystem in which the community is actively involved in its implementation.

Numerous CFPPs worldwide have started using biomass as an alternative to partially replace coal in co-firing systems. It is also well known that using coal-biomass co-firing power production technology reduces greenhouse gas (GHG) emissions (Nonaka et al., 2011; Teixeira et al., 2014; Umar & Rohayati, 2021; Klein-

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hans et al., 2018; Preradovic et al., 2023). However, there are specific issues with co-firing technology. Raw biomass has a high content of moisture, low bulk density, low heating value, and varying composition (Singh et al., 2016). Furthermore, biomass exhibits hydrophilic characteristics, rendering it weather-sensitive. Unprocessed biomass has the propensity to break down rapidly. Furthermore, storing new biomass promotes microbe development and material decomposition (Álvarez et al., 2018). One of the most promising methods for valuing biomass is torrefaction, sometimes called high-temperature drying or low-temperature pyrolysis (Stępień et al., 2017; Ribeiro et al., 2018). Torrefaction is conducted at temperatures between 300 and 400°C at atmospheric pressure in an oxygen-free environment (Bajcar et al., 2018; Doddapaneni & Kikas, 2023). The absence of oxygen prevents torrefied biomass's thermal breakdown, thus preventing combustion (Chen et al., 2015).

This research used abundant rice husk biomass and sub-bituminous coal to ensure supply. Rice husk refers to the outer shell of rice grains separated from the rice through milling. In several areas of Indonesia, rice husks are used as an alternative fuel for producing husk charcoal. People use husk charcoal as a cooking fuel or a mixture to make organic fertilizer.

The primary goal of this study was to determine the optimal temperature and residence time for the rice husk torrefaction process. Given the lack of existing knowledge on this topic, especially for rice husks from Indonesia, we conducted this study to enhance the calorific value and minimize the incidence of ash deposition during coal-rice husk combustion in a co-firing system.

2. Material and Methods

2.1. Coal characterization

This study used sub-bituminous coal from South Sumatra as a coal sample. The coal sample was milled and sieved through a 250- μ m (No. 60) sieve to determine its proximate, ultimate, and calorific values. The proximate of inherent moisture (IM), ash, volatile matter (VM), and fixed carbon (FC) were according to the ASTM D7582-15 Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis.

In thermogravimetric analysis, a sample's mass is regularly measured as a function of temperature in a controlled environment. A coal sample of about 1 g is used (Song et al., 2017). The system continuously tracked every mass measurement during the process. The temperature of the furnace is raised to 110°C and maintained isothermally. This guarantees that the moisture in the coal was the cause of any mass loss. Then, it is ramped up to 900°C and maintained isothermally. The volatiles' disappearance entirely caused this isotherm re-

gion's mass reduction. In a nitrogen atmosphere, the first two processes are carried out. The third section uses oxygen as the atmosphere. The remaining material was collected as ash once the coal had burned entirely. Every analysis was completed when the sample reached a consistent mass as indicated by the device's parameters. Fixed carbon was determined indirectly by subtracting the total value of ash, and volatile matter from 100, as in Equation 1 (Speight, 2005).

$$FC = 100 - IM - Ash - VM \quad (1)$$

The ultimate analysis was conducted according to ASTM D3176-08, Standard Practice for Ultimate Analysis of Coal and Coke. In this analysis, a coal sample was combusted in an ultimate analyzer, which measures the weight percent of total carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) at the same time from the same sample in the analyzer. The oxygen (O) was estimated by difference, as in Equation 2.

$$O = 100 - C - H - N - S - Ash \quad (2)$$

The calorific value measures the amount of energy produced from a unit weight of coal when combusted in oxygen. A measured sample of coal was completely combusted in a bomb calorimeter, a device for measuring heat (ASTM method D5865-04 Standard Test Method for Gross Calorific Value of Coal and Coke). One gram of coal was put into a metal sample cup. After that, the cup was inserted into a retaining slot between two electrodes that protruded from a stainless steel container's cover. A thin, loop-shaped metal wire fuse was affixed to the electrodes and inserted into the coal sample. After that, the electrode and cup were inserted into the "bomb"-shaped container. Subsequently, the bomb containing the sample was placed in a water bath, and the sample was ignited within the bomb using an electrical current. The water bath was heated as a result of the sample's ignition. The calorific value of the sample was determined based on the change in water-bath temperature.

The main chemical components of the coal ash are identified as silica, alumina, iron oxide, and alkalis of SiO₂, Al₂O₃, Fe₂O₃, TiO₂, P₂O₅, CaO, MgO, Na₂O, K₂O, MnO, and SO₃ (Trivedi & Sud, 2004). The sample of ash was melted using Lithium Meta Borate (LiBO₂) at 900°C. After melting, the sample was dissolved with HNO₃. This solution was examined for various elements following Standard Analytical Procedures (Medham et al., 2000). For the SO₃ determination, it was dissolved separately with HNO₃ which previously the sample was mixed with KBR. The SiO₂ was determined by gravimetry, the Al₂O₃, Fe₂O₃, CaO, MgO, Na₂O, K₂O, and MnO were determined by Atomic Absorption Spectrometry (AAS), TiO₂, and P₂O₅ were determined by spectrophotometry and SO₃ by turbidimetry (Yu et al., 2012).

2.2. Rice husk torrefaction

The raw rice husk sample was obtained from a rice mill in the Bandung Regency area (sample mark: RS). The rice husk sample was washed with water before tor-

refaction to remove impurities like soil and dust, then was dried in an oven at 200°C for 2 hours and cooled to room temperature. To be characterized, the rice husk sample was milled and sieved to pass 250 µm.

In our previous research, a palm kernel shell (PKS) biomass was used. The torrefaction process was carried out at a temperature of 450°C for 1 hour (Umar et al., 2024). This torrefaction temperature, if applied to rice husks, will be overheated because rice husks are more flammable than PKS. In literature, the optimum torrefaction process of rice husk was 360°C (Tsai et al., 2021). In this study, the experimental variables were carried out at temperatures of 300, 350, and 400°C, and residence times of 30, 60, and 90 minutes. The experiment was done at room temperature and free of oxygen.

The rice husk sample was put in a closed container and heated at the specified temperature and time according to the experimental variables. The design of the experiment is shown in Table 1. The torrefied rice husk was then cooled, milled, and sieved for characterization. The raw and torrefied rice husks were characterized by

Table 1: Rise husk torrefaction experimental design

Experiment	Temperature °C	Time minutes	Torrefied rice husk Sample code
1	300	30	TR-303
2	300	60	TR-306
3	300	90	TR-309
4	350	30	TR-353
5	350	60	TR-356
6	350	90	TR-359
7	400	30	TR-403
8	400	60	TR-406
9	400	90	TR-409

Table 2: Proximate, ultimate, and calorific values on air dried basis

	Raw	Torrefied rice husk								
		TR-303	TR-306	TR-309	TR-353	TR-356	TR-359	TR-403	TR-406	TR-409
IM. %	10.4	2.84	2.75	2.77	2.62	2.66	4.22	2.16	2.14	1.09
Ash. %	21.7	46.34	46.22	46.31	42.60	42.34	42.98	51.85	44.91	51.05
VM. %	54.65	23.49	23.41	23.47	22.57	22.24	20.39	20.67	20.1	18.32
FC. %	13.25	27.33	27.62	27.45	32.21	32.76	32.41	25.32	32.85	29.54
C. %	33.29	37.55	37.61	37.64	37.74	37.8	37.66	28.06	35.88	32.67
H. %	5.25	2.92	2.87	2.84	2.89	2.93	2.26	1.89	2.63	2.13
N. %	nd	0.1	0.12	0.11	0.08	0.08	0.15	0.18	0.06	0.14
S. %	0.14	0.04	0.03	0.04	0.04	0.02	0.04	0.04	0.02	0.03
O. %	39.62	13.05	13.15	13.06	16.65	16.83	16.91	17.98	16.5	13.98
CV cal/g	3,107	3,257	3,316	3,264	3,383	3,401	3,331	2,932	3,255	2,817
CV MJ/kg	14,529	14,406	14,287	14,066	14,556	14,640	14,572	9,858	13,937	11,933

Note: nd, not detected

Table 3: Ash chemical composition analysis results on weight percent (w %)

	Raw	Torrefied rice husk								
		TR-303	TR-306	TR-309	TR-353	TR-356	TR-359	TR-403	TR-406	TR-409
SiO ₂	94.53	96.68	96.71	96.82	96.75	96.8	97.4	97.2	96.35	96.9
Al ₂ O ₃	0.22	0.071	0.068	0.066	0.077	0.069	0.064	0.069	0.081	0.081
Fe ₂ O ₃	0.17	0.06	0.062	0.074	0.075	0.18	0.76	0.061	0.078	0.71
K ₂ O	2.1	0.72	0.69	0.67	0.7	0.62	0.58	0.6	0.6	0.62
Na ₂ O	0.052	0.008	0.007	0.007	0.007	0.007	0.006	0.007	0.011	0.02
CaO	0.43	0.64	0.68	0.70	0.37	0.69	0.71	0.7	0.84	0.94
MgO	0.33	0.24	0.23	0.24	0.25	0.26	0.26	0.26	0.32	0.34
MnO	0.15	0.12	0.12	0.13	0.12	0.14	0.12	0.12	0.12	0.12
TiO ₂	0.013	0.004	0.004	0.005	0.005	0.004	0.004	0.003	0.006	0.004
P ₂ O ₅	0.63	0.16	0.17	0.15	0.15	0.19	0.18	0.15	0.17	0.14
SO ₃	0.19	0.098	0.04	0.028	0.13	0.03	0.03	0.032	0.028	0.031

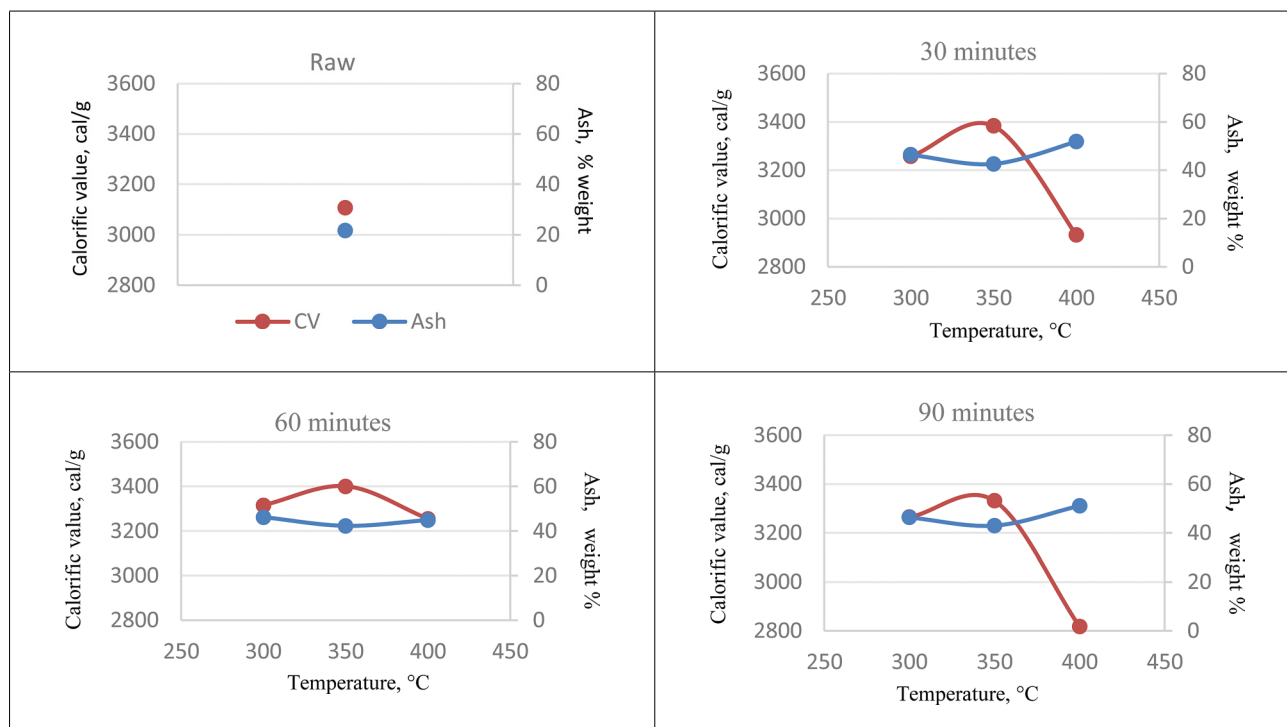


Figure 1: Effect of processing temperature on ash content and calorific value

proximate, ultimate, calorific value, and chemical ash composition according to the standards used for coal analysis above.

2.3. Coal-torrefied rice husk characterization

The torrefied rice husk at optimum temperature and time was blended with coal in several compositions, with the ratios of coal to rice husk in weight percentages of 95:5, 90:10, 85:15, 80:20, and 75:25, respectively. The proximate, ultimate, calorific value and ash chemical composition of the blended coal-rice husk were calculated based on the analysis results of each composition. The characterization of the blended coals was investigated to study the impact of rice husk torrefaction on ash deposition in a co-firing system.

3. Results and Discussion

Table 2 shows the proximate, ultimate, and calorific value analysis results, and **Table 3** shows the ash chemical composition of the raw and torrefied rice husk at several temperatures and residence times.

3.1. Effect of temperature on the torrefaction process

The inherent moisture content was drastically dropped due to the torrefaction process, resulting in only 1–3% for the torrefied rice husk. Furthermore, the torrefied biomass lost the hydroxyl groups required for moisture binding and absorption. Consequently, the characteris-

tics of the biomass change from hygroscopic to hydrophobic (Ribeiro et al., 2018).

The volatile matter content of the rice husk significantly decreased after the torrefaction process. Regarding the volatile materials, it was observed that the volatiles decreased as the process temperature rose. Matali et al. also looked into this dependence (Matali et al., 2016). Fuels with a lower volatile matter content were more difficult to ignite. Because of this, additional energy had to be applied to the torrefied rice husk to start the auto-ignition process. More flammable and luminescent compounds from the fuel were released during the thermal processing at the higher torrefaction temperature (Dyjakon et al., 2019).

The raw rice husk ash content was 21.7%. After the torrefaction process, the ash content was higher. The temperature during the torrefaction process correlated with the ash amount, as shown in **Figure 1**. A portion of the volatile stuff was released due to the higher temperature. The consequence was an increase in the fuel's ash content due to solid material concentration (Stepień et al., 2017). The ash content of torrefied rice husk rose at 300°C at each processing time, then decreased when the temperature was increased to 350°C and rose again at a temperature of 400°C. The rise in ash content when heated to 400°C might be caused by excessive heat so that some of the biomass becomes ash. The lowest ash content was achieved by torrefied rice husks at a temperature of 350°C at each processing time.

Concerning the impact of the torrefaction process temperature on the torrefied rice husk's calorific value,

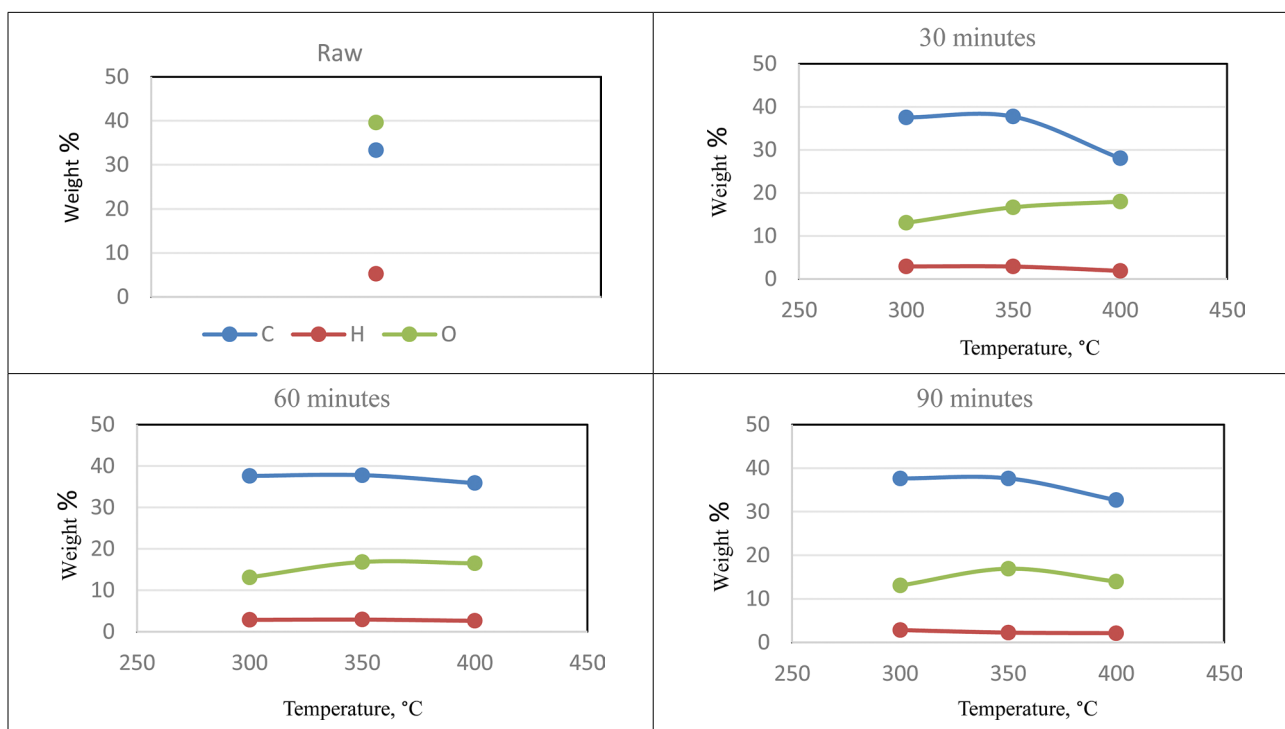


Figure 2: Effect of processing temperature on carbon, hydrogen, and oxygen content

the calorific value rose from 300 to 350°C and then decreased again at 400°C. The increase in ash content correlated with this decrease in calorific value. The heating value decreased as the residence time of the torrefaction process increased from 60 to 90 minutes at 400°C. This decrease resulted from reduced volatile matter and increased ash content caused by excessive heat.

After the torrefaction process, the rice husk's carbon content increased. When the torrefaction process reaches a temperature of 350°C, the carbon content increases; at 400°C, it decreases. The carbon content in torrefied rice husks at a temperature of 400°C for 30 minutes was lower than that of raw coal (see **Figure 2**). Overheating the torrefaction process resulted in a significant increase in ash content, leading to a decrease in fixed carbon, including elemental carbon. Compared to carbon, the proportion of oxygen and hydrogen has also decreased. The Van Krevelen diagram in **Figure 3** (Nunes et al., 2018) illustrates how the H/C and O/C atomic ratios decreased and approached coal after torrefaction.

The chemical composition of biomass ash is the primary factor influencing ash deposition. We used the non-combustible components created when burning biomass to acquire the ashes' chemical composition in oxide form. The primary factors influencing the formation of slag are Fe_2O_3 , CaO , MgO , K_2O , Na_2O , SiO_2 , Al_2O_3 , and TiO_2 (Samsudin et al., 2021). There were three types of oxides found: bases (Na_2O , K_2O , CaO , MgO , and MnO), amphoteric oxides (Al_2O_3 and Fe_2O_3), and acids (SiO_2 , TiO_2 , and P_2O_5). Alternatively, we can divide these oxides into two groups: Al_2O_3 belongs to the

acidic oxide group, while Fe_2O_3 belongs to the basic oxide group (Zierold & Odoh, 2020).

Figure 4 illustrates the effect of the torrefaction processing temperature on the basic and acidic oxides. The acidic oxides of the torrefied rice husk were higher than those of the raw husk, and the basic oxides were lower than those of the raw husk. At a residence time of 30 minutes, acidic oxide increased with an increase in temperature. Meanwhile, at residence times of 60 and 90 minutes, it increased at temperatures of 300 and 350°C and declined when the temperature was 400°C. Unlike the acidic oxides, the basic oxides, at a residence time of 30 minutes, decreased when the temperature rose from 300 to 350°C and increased again if the temperature rose to 400°C. The basic oxides at a residence time of 60 and 90 minutes slightly increased with an increase in temperature.

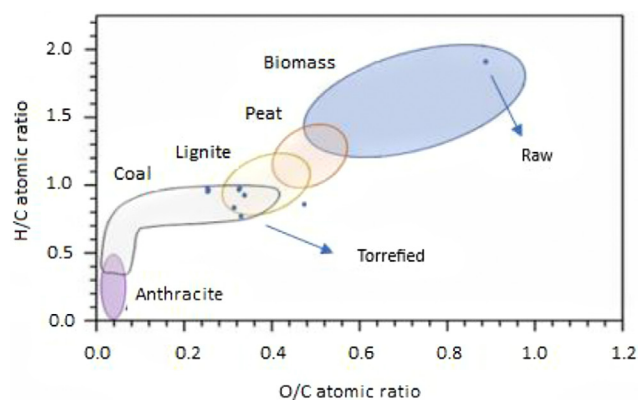


Figure 3: Van Krevelen's diagram of raw and torrefied rice husk (Nunes et al., 2018)

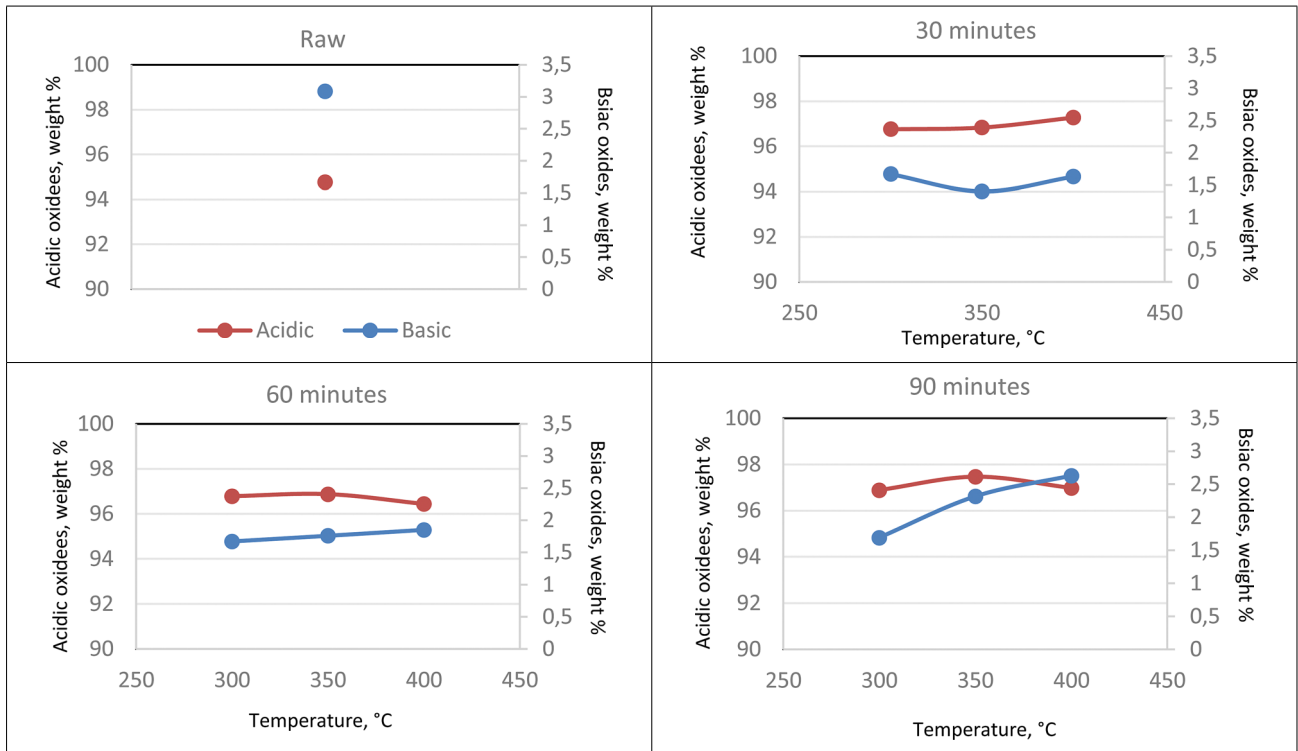


Figure 4: Effect of processing temperature on basic and acidic oxides

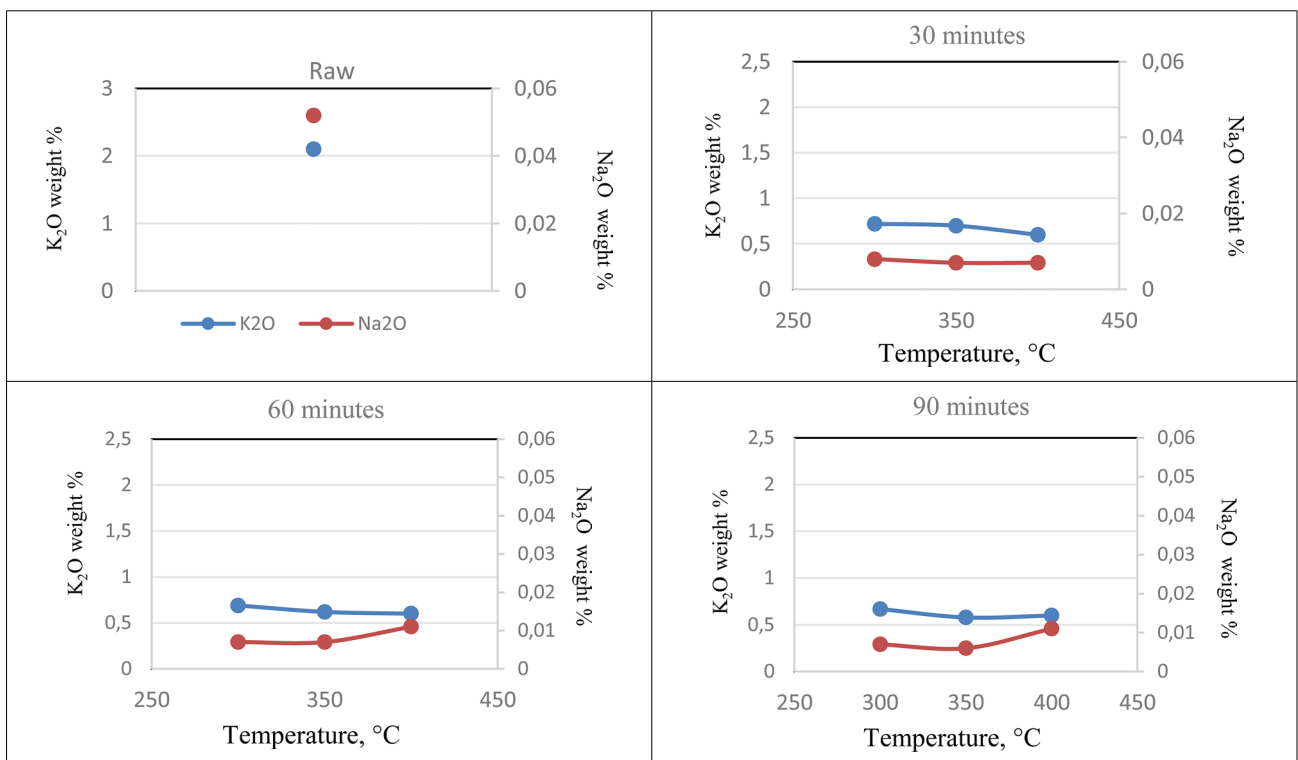


Figure 5: Effect of processing temperature on potassium and sodium oxide contents

With the increase of acid oxides and the decrease of basic oxides, the basic-acidic ratio (B/A) decreases. The ratio of B/A was defined based on Equation 3. The ash has low slagging when B/A is less than 0.5,

medium when B/A is between 0.5 and 1, high when B/A is between 1 and 1.75, and severe when B/A exceeds 1.75. Thus, we anticipate a decrease in the propensity for ash deposition, slagging, and fouling when burning coal

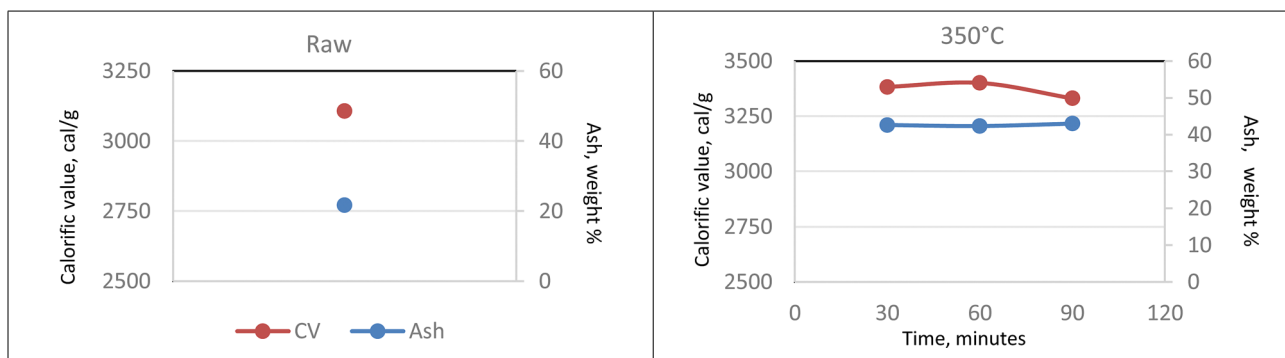


Figure 6: Effect of residence time on ash content and calorific value

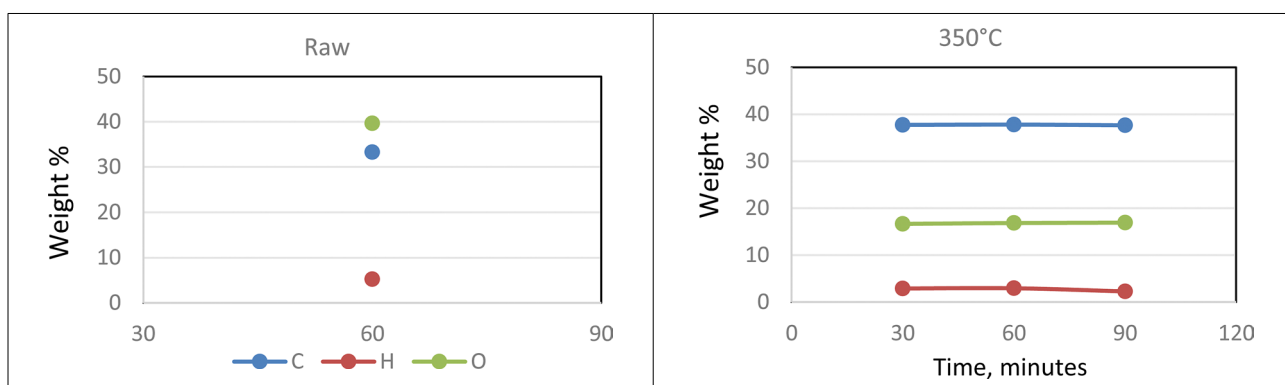


Figure 7: Effect of residence time on carbon, hydrogen, and oxygen contents

and rice husks in a co-firing system (Kamara et al., 2022).

$$\frac{B}{A} = \frac{(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)}{(SiO_2 + Al_2O_3 + TiO_2)} \quad (3)$$

There are several reasons why the application of the co-firing technique for coal and biomass is currently limited worldwide. Some of these are brought on by corrosion and ash deposition resulting from elevated amounts of alkali metals potassium (K) and sodium (Na) within biomass (Liu et al., 2022). When high alkali biomass is utilized thermally, some alkali metals are released into the flue gas. The ash deposition layer increases due to the released alkali metals condensing and forming a sticky layer on the heat transfer surface at relatively low temperatures (Liu et al., 2018). This case causes the heat transmission capacity to decrease, heat loss to increase, boiler operation to deviate, and boiler efficiency to drop significantly (Mlonka-Mędrala et al., 2019). The effect of the temperature torrefaction process on alkali oxide contents, especially potassium and sodium, can be seen in Figure 5.

The potassium and sodium oxides of rice husk decreased due to the torrefaction process. Potassium contents decreased by increasing the processing temperature, while sodium content decreased when the temperature rose from 300 to 350°C but increased again if the temperature rose to 400°C. This case is in line with the

literature review (Li et al., 2016) that states that the transformation behavior of alkali metals is influenced by reaction conditions such as atmosphere combustion, reaction time, temperature, pressure, etc.

From these findings, it is possible to assume that ideal circumstances for the rice husk torrefaction process were achieved at a temperature of 350°C for 60 minutes. This result follows a statement by (Nunes et al., 2018) that 250–350°C is the ideal temperature range for biomass torrefaction for 0.5 to 2 hours. Therefore, the process at 400°C was too high.

3.2. Effect of residence time on the torrefaction process

The torrefaction process was conducted at 300, 350, and 400°C temperatures for 30, 60, and 90 minutes. As previously discussed, the temperature optimum of the process was achieved at 350°C. Therefore, we would only explore the influence of the residence time at 350°C. Figure 6 illustrates how the residence time affected the ash content and calorific value. It shows that at a temperature of 350°C, the residence time had no discernible change in ash content. The ash content slightly decreased when the residence time was extended to 60 from 30 minutes, then slightly increased at 90 minutes. So, the calorific value increases upon extending the residence time from 30 to 60 minutes and decreases if the residence time increases to 90 minutes. A rise fol-

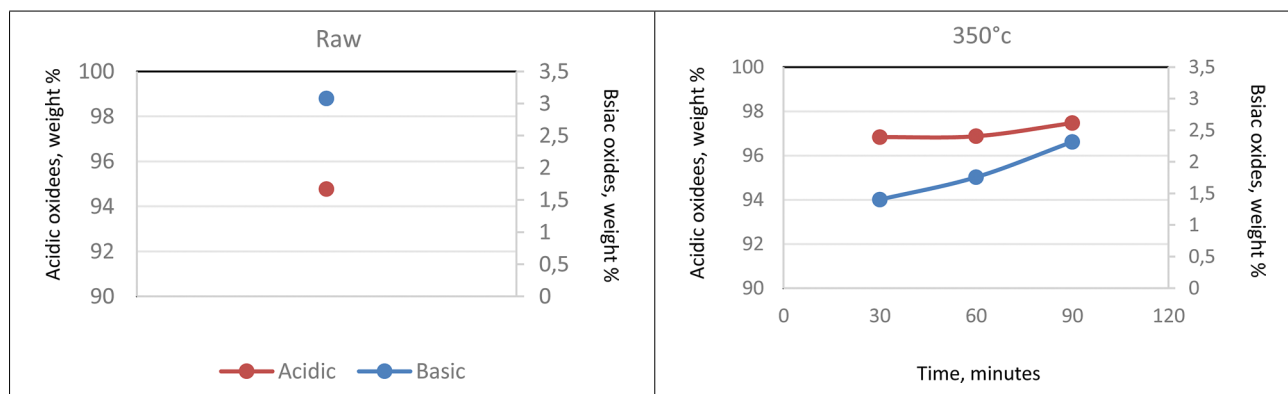


Figure 8: Effect of processing time on basic and acidic oxides

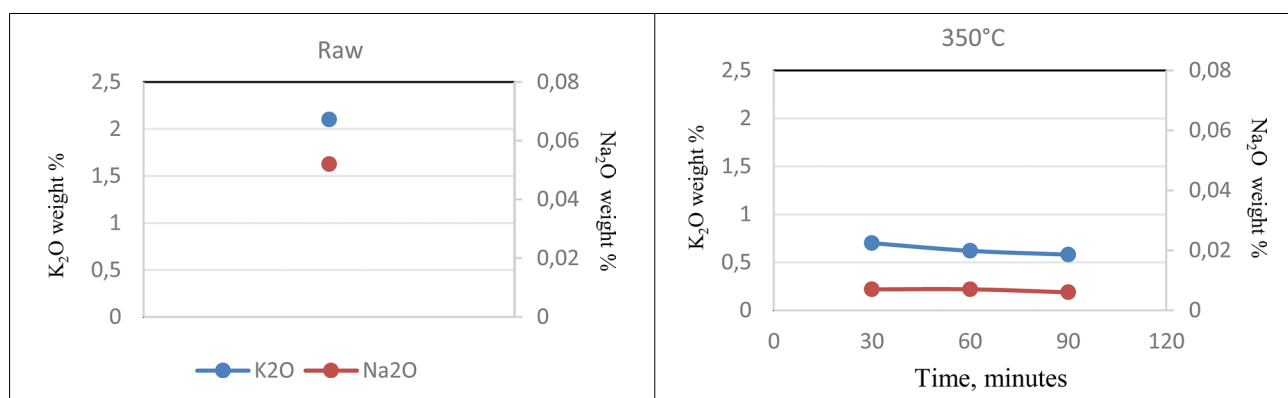


Figure 9: The impact of processing time on potassium and sodium oxide content

lowed the decrease in heating value in the ash content. Despite the amount of ash, the residence time did not significantly affect the torrefied rice husk’s carbon, hydrogen, and oxygen content at a temperature of 350°C, as shown in Figure 7.

The carbon content rose from 30 to 60 minutes and then dropped at 90 minutes. While hydrogen content remained mainly constant over time, oxygen content decreased as time was extended. After the torrefaction process, the atomic ratio of O/C and H/C decreased due to the rising carbon content and decreasing oxygen and hydrogen. As a result, the torrefied rice husk was similar to sub-bituminous coal, as illustrated in Figure 3 of van Krevelen’s diagram.

Figure 8 illustrates how the residence time affects acidic and basic oxides. These oxides affect the B/A ratio, which causes ash deposition in a boiler when the biomass is burned (Kamara et al., 2022).

At 350°C, the acidic oxide slightly increased with an increase in residence time from 30 to 60 minutes and significantly increased at 90 minutes. Meanwhile, the basic oxide increased with the increase in residence time. This means that a longer residence time causes an increase in basic oxide and the ratio of B to A. Therefore, the tendency for ash deposition also increases.

Potassium oxide contents decreased with increased residence time, whereas sodium oxide content remained

relatively unchanged, as shown in Figure 9. Based on the results and discussions, the optimum condition of the rice husk torrefaction was achieved at 350°C for 60 minutes.

3.3. Coal-torrefied rice husk blending

Coal was blended with rice husk that had been torrefied at a temperature of 350°C for 60 minutes to study the characteristics of blended coal and rice husk as fuel in a co-firing system. This study aims to replace a portion of coal with torrefied rice husks as boiler fuel for electricity or other industries. As a fuel, coal’s calorific value should be high to ensure high combustion efficiency. Therefore, emissions from coal combustion can be reduced. The coal’s calorific content strongly impacts the boiler’s efficiency and dependability. Therefore, to prevent more severe damage, appropriate maintenance actions are required (Yudisaputro et al., 2022).

Table 4 displays the results of blended coal-torrefied rice husks’ proximate, ultimate, and calorific value analyses. The sample code CTR 95:5 means that the ratio in weight of coal was 95% and torrefied rice husk was 5%; likewise for the following code. The analysis results of proximate, ultimate, and calorific values were calculated based on each result’s composition.

To obtain the blended coal-torrefied rice husks having a heating value greater than 5,000 cal/g, adding the torrefied biomass to the coal was no more than 10% in

Table 4: The proximate, ultimate, and calorific value of the blended coal and torrefied rice husks

	Coal	TR-356	CTR 95:5	CTR 90:10	CTR 85:15	CTR 80:20	CTR 75:25
IM. %	9.14	2.66	8.82	8.49	8.17	7.84	7.52
Ash. %	12.45	42.34	13.94	15.44	16.93	18.43	19.92
VM. %	39.59	22.24	38.72	37.86	36.99	36.12	35.25
FC. %	38.82	32.76	38.52	38.21	37.91	37.61	37.31
C. %	55.82	37.80	54.92	54.02	53.12	52.22	51.32
H. %	5.17	2.93	5.06	4.95	4.83	4.72	4.61
N. %	0.50	0.08	0.48	0.46	0.44	0.42	0.40
S. %	0.75	0.02	0.71	0.68	0.64	0.60	0.57
O. %	25.31	16.83	24.89	24.46	24.04	23.61	23.19
CV cal/g	5,257	3,401	5,164	5,071	4,979	4,886	4,793

weight. This composition has a calorific value of 5,071 cal/g, 8.49% inherent moisture, 15.44% ash content, and 38.21% fixed carbon (see **Table 4**).

According to the chemical composition of the ash, various indices can be used to assess the ash deposition tendency of the fouling index (Fu) and slagging/Babcock index (Rs). Slagging and fouling are related to the accumulation of deposits in a boiler. Slagging typically occurs on the furnace walls due to the melting or softening of ash particles caused by high temperatures, forming slag deposits. In areas with low flue gas velocity, like at the boiler's heat transfer surfaces, the possibility of slagging is high. The accumulation of ash, soot, or other solid particles can form a layer on the surfaces. Both slagging and fouling reduce heat transfer efficiency and potentially lead to corrosion (**Panagiotidis et al., 2015**).

The fouling index's base ratio is B/A, highly dependent on the potassium and sodium oxide content (**Yang et al., 2017**) predict that low fouling tendencies, defined as a mild fouling tendency between 0.6 and 40 and a solid fouling propensity above 40, occur when the value of Fu is less than 0.06. The content of sulphur on a dry basis and the coal ash ratio of B to A were used to predict the Babcock slagging index (Rs) during the boiler operation. Higher Rs levels suggest a higher slagging propensity (**Kamara et al., 2022**). A low slagging tendency occurs for values of Rs less than 0.3, between 0.6 and 2.0 is medium, and severe for Rs greater than 2.6.

The Bed Agglomeration Index (BAI) was applied to assess issues during the combustion of fluidized beds. Bed agglomeration occurs when the BAI is less than 10 (**Lee et al., 2017**). A high SR index indicates low slagging due to its high slag viscosity. When the SR exceeds 72, contaminants are less likely to occur. The potential to generate contaminants averages out when the range of SR index is from 65 to 72. The propensity to produce contaminants is quite strong if the SR index is below 65 (**Yang et al., 2019**). The BAI, Fu, SR, and Rs were determined using **Equations 4–7**.

$$Fu = \frac{B}{A} \times (Na_2O + K_2O) \quad (4)$$

Table 5: Ash chemical composition of the blended coal-raw and coal-torrefied rice husks

	Coal	Raw rice husk	Blended coal-raw rice husk 90:10	Torrefied rice husk	Blended coal-torrefied rice husk 90:10
SiO ₂	93.21	94.53	93.34	96.8	93.57
Al ₂ O ₃	4.01	0.22	3.63	0.069	3.62
Fe ₂ O ₃	1.28	0.17	1.17	0.18	1.17
K ₂ O	0.17	2.1	0.36	0.62	0.22
Na ₂ O	0.03	0.052	0.03	0.007	0.03
CaO	0.50	0.43	0.49	0.69	0.52
MgO	0.13	0.33	0.15	0.26	0.14
MnO	0.02	0.15	0.03	0.14	0.03
TiO ₂	0.08	0.013	0.08	0.004	0.08
P ₂ O ₅	0.01	0.63	0.07	0.19	0.03
SO ₃	0.28	0.13	0.27	0.14	0.27
LOI	0.68	0.53	0.67	0.73	0.69
SO ₃	0.07	0.19	0.08	0.03	0.07
B/A	0.02	0.03	0.02	0.02	0.02
Fu	0.11	0.02	0.10	0.03	0.10
Rs	0.02	0.0046	0.015	0.0004	0.015
BAI	6.37	0.03	5.74	0.29	5.76
SR	97.99	99.03	98.10	98.85	98.08

$$Rs = \frac{B}{A} \times (S) \quad (5)$$

$$BAI = \frac{Fe_2O_3}{Na_2O + K_2O} \quad (6)$$

$$SR = \frac{SiO_2 \times 100}{SiO_2 + Fe_2O_3 + CaO + MgO} \quad (7)$$

Table 5 displays the chemical ash composition result which includes the ash deposition tendencies of fouling, slagging, bed agglomeration, and slag viscosity of the blended coal-raw husk and coal-torrefied rice husk, which were torrefied at 350°C for 60 minutes with a 90:10 weight ratio of coal to rice husk.

Both the used coal and rice husk have a high SiO₂ content, which is why the blend of coal and rice husk also has a high SiO₂ content. High SiO₂ coal has a high ash fusion temperature, so the ash deposition tendency is low (Li et al., 2013). Coal ash with a high iron content encourages the deformation of liquids and the transformation of Fe³⁺ into Fe²⁺. Furthermore, the content of Fe₂O₃ in coal ash influences its feasibility under various circumstances. As the iron content decreases, the potential for ash deposition to occur reduces (He et al., 2022).

At a composition of coal and both raw and torrefied rice husks (90:10), the tendency of ash deposition remains almost the same. However, the torrefaction process reduces the presence of some basic oxides that influence ash deposition. However, torrefaction has several advantages compared to other biomass conversion technologies. It can improve biomass's fuel characteristics, making it a more suitable option for energy production. It is easier to mix liquefied biomass with coal because it has better physical properties, like being able to be ground into ash and not attracting water (Doddapaneni & Kikas, 2023; Preradovic et al., 2023), and it also has higher heating values and energy densities.

4. Conclusion

The research results and discussion indicate that the process reached its optimal condition at a temperature of 350°C and a residence time of 60 minutes. In this condition, the torrefied rice husk has a calorific value of 3,401 cal/g, an inherent moisture content of 2.66%, and an ash content of 42.34%. Based on the O/C and H/C atomic ratios, the torrefaction process raised the quality of the rice husk to be similar to that of the sub-bituminous coal. To get a calorific value of >5,000 cal/g, the torrefied rice husk added to the coal should not exceed 10% in weight. When combined with coal, the rice husk torrefaction process slightly affects ash deposition. However, torrefied rice husk has a higher calorific value, resulting in higher combustion efficiency and lower moisture content, reducing volume, transportation, and storage costs. In addition, rice husk resulting from the torrefaction process is more straightforward to grind and blend with coal, thereby reducing handling costs.

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SAŽETAK

Torefikacija rižine ljuske kao priprema za suspaljivanje ugljena i biomase i njezina sklonost taloženju pepela

Ugljen se u Indoneziji najviše koristi za proizvodnju električne energije. Zbog sve veće zabrinutosti oko klimatskih promjena i potrebe za smanjenjem emisija uzrokovanih izgaranjem ugljena, goriva temeljena na biomasi postaju sve konkurentnija. Proces karbonizacije biomase za proizvodnju krutoga goriva, ili torefikacija, uveden je drugdje. U ovome istraživanju korišteni su subbitumenski ugljen i rižine ljuske s obzirom na velik potencijal tih resursa koji Indonezija posjeduje. Primarni cilj ovoga istraživanja bio je odrediti optimalnu temperaturu i vrijeme zadržavanja za proces torefikacije rižine ljuske s namjerom da se smanji sadržaj alkalnih oksida koji dovode do taloženja pepela. To je bilo potrebno zbog ograničenih dostupnih informacija, osobito za lokalne rižine ljuske iz Indonezije. Proveli smo torefikaciju rižine ljuske na temperaturama od 300, 350 i 400 °C tijekom 30, 60 i 90 minuta. Rezultati pokazuju da su optimalni uvjeti pri temperaturi od 350 °C i vremenu zadržavanja od 60 minuta. U tome stanju smanjili su se kalijevi i natrijevi oksidi, a povećala kalorijska vrijednost. Da bi se dobila mješavina ugljena i rižine ljuske s kalorijskom vrijednošću većom od 5000 cal/g (ADB), udio ugljena i rižine ljuske trebao bi redom biti 90 % odnosno 10 %. Proces torefikacije rižine ljuske nije imao velik utjecaj na pojavu taloženja pepela. Međutim, proces torefikacije povećao je kalorijsku vrijednost, smanjio troškove transporta zbog nižega sadržaja vlage i poboljšao mljevenje tako da se lako miješao s ugljenom.

Ključne riječi:

torefikacija, temperatura, vrijeme zadržavanja, lužina, taloženje pepela

Author's contribution

Datin Fatia Umar (1) (Research Professor, Ph.D., Chemical Science and Engineering) provided the idea and methodology, conceptualization, interpretation, presentation of the results, research management, and writing, reviewing, and editing of the paper. **Zulfami, Zulfahmi (2)** (Researcher, Ph.D., Geological Engineering) data visualization, and writing and editing of the paper. **Liston Setiawan (3)** (Researcher, Bachelor, Mining Engineering) performed the fieldwork, and visualization of the data. **Gunawan, Gunawan (4)** (Researcher, Bachelor, Mining Engineering) performed the fieldwork, and visualization of the data. **Agus Prakosa (5)** (Researcher, Bachelor) visualization of the data, and reviewed the paper. **Truman Wijaya (6)** (Researcher, Bachelor, Geological Engineering) prepared the samples, and visualization of the data, **Edwin Akhdiat Daranin (7)** (Researcher, Magister, Geological Engineering) prepared the samples and reviewed the paper.