

Two-stage palm kernel shell washing with water and acetic acid as preparation of co-firing system with coal

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 62-91
DOI: 10.17794/rgn.2024.1.1

Original scientific paper



Datin Fatia Umar¹, Zulfahmi Zulfahmi², Suganal Suganal³, Nendaryono Madiutomo⁴, Truman Wijaya⁵, Miftahul Huda⁶, Liston Setiawan⁷, Edwin Akhdiat Daranin⁸, Gunawan Gunawan⁹ and Ika Monika¹⁰

¹ Researcher, Mining Technology Research Centre, Agency of National Research and Innovation, The Republic of Indonesia, Jalan Sutami KM 15, Tanjung Bintang 35361, Lampung, Indonesia, <https://orcid.org/0000-0002-7401-4478>

²⁻¹⁰ Researcher, Mining Technology Research Centre, Agency of National Research and Innovation, The Republic of Indonesia, Jalan Sutami KM 15, Tanjung Bintang 35361, Lampung, Indonesia

Abstract

Palm kernel shells (PKS) were washed with water and glacial acetic acid (CH_3COOH) gradually to prepare them for co-firing with coal. They were then torrefied at 450°C for one hour. Washing was done to reduce the concentration of ash and alkaline oxides, which would reduce the chance of slagging and fouling. The research was conducted considering that information about washing the PKS with acetic acid and then having them torrefied is very limited and unclear. The results showed that washed and torrefied PKS had better characteristics than those of raw PKS or PKS washed with water. PKS that is washed with acid, torrefied and then blended with coal has low slagging and medium fouling tendencies. However, based on ash fusion temperature, the inclination towards slagging and fouling is high under reducing conditions and medium under oxidation conditions.

Keywords:

washing; torrefaction; slagging; fouling; ash fusion temperature

1. Introduction

Indonesia has 143.7 billion tons of coal resources, with total reserves of 38.84 billion tons (Wibisono et al., 2019). Currently, coal is used most extensively in Indonesia, about 80% is used as fuel for coal-fired power plants (CFPPs), and the rest is distributed to the cement, metallurgical, paper, textile, and other industries.

The United Nations Conference on Climate Change in Glasgow, Scotland, in 2021 resulted in an agreement called the Glasgow Agreement (COP 26), which included efforts regarding the gradual cessation of coal energy use to achieve NZE (Net-zero Emission). Coal is the highlight because it is one of the major causes of carbon emissions, which can drive the rate of increase in the Earth's temperature. Coal contributes around 40% of annual CO_2 emissions, therefore reducing emissions globally by 45% by 2030 and almost completely by the middle of the century depend on it. At the conference, Indonesia also committed to the agreement on the global coal transition towards clean energy to phase out the use of coal by 2040 (Indonesia, 2021).

Despite its shortcomings, coal remains important as a fuel in industry for its product processes. To address the conflict between industrial expansion and environmental protection, outdated fuel-burning technology needs to be improved. One of the actions that can be taken to reduce coal usage while fulfilling energy demand is by applying coal-biomass co-firing technology. By applying this technology, coal-fired power plants (CFPP) or other industries can continue to operate at full capacity to meet demand, while CO_2 emissions are expected to be reduced.

Across the world, several CFPPs have started using biomass in place of coal in the co-firing system as an alternate method of using coal sustainably. Because of their brief life cycles, biomass fuels are assumed to be renewable and carbon-neutral. It might not be a desirable solution from an economic or logistical standpoint for a large power plant to use biomass as its exclusive fuel source, but biomass can be used in addition to more traditional fossil fuels as a supplemental fuel. The effectiveness of coal-biomass co-firing power generation technology in lowering greenhouse gas (GHG) emissions has also been well-established (Nonaka, Hirajima, and Sasaki, 2011; Teixeira et al., 2014; Umar and Rohayati, 2021; Kleinhans et al., 2018).

There are numerous issues and difficulties in the power generation process using coal and biomass. Signifi-

Corresponding author: Datin Fatia Umar
e-mail address: dati001@brin.go.id

cant drawbacks for biomass power plants are the high cost of raw biomass and the high operating costs of the feedstock supply chain process. Many proven coal-biomass co-firing technologies for power generation are available around the world, but to ensure that these technologies can be applied to specific coals and biomass, in-depth studies are needed. Boiler efficiency varies due to varied ratios of co-combustion with biomass fuels, which also affect the degree of boiler corrosion and slagging. To explore the feasibility of performing coal-biomass co-firing using coal and biomass that comply with the circumstances of power plants in Indonesia, scientific determination of the biomass type and co-firing ratio is necessary.

There are, however, some problems with co-firing technology. These include deposition and corrosion caused by the high concentration of alkali metals in biomass, especially potassium (Q. Liu et al., 2022). With a high concentration of potassium in biomass, during the co-firing process, alkaline substances (e.g. KCl) change into the phase of gas, which causes ash accumulation, deposition, and rust on the boiler's heated surface, leading to a reduction in the heat transmission capacity, increased heat loss, deviations in the boiler's operation, and significantly decreased boiler efficiency (Mlonka-Mędrala et al., 2019; Lupiáñez et al., 2016). Melts at low temperatures and erratic alkali metal combinations are produced during co-firing when the biomass's alkali metal content and the coals' inorganic minerals combine, creating a more complex ash composition. Therefore, biomass processing is very important to overcome the slagging and fouling problem.

Fouling and slagging are frequent issues when burning biomass (Lachman et al., 2021). Slagging and fouling are intricate processes that have been the subject of numerous investigations, including those by Teixeira et al. (2012), Yao et al. (2017), and Tortosa-Masiá et al. (2005). Kleinhans et al. (2018) addressed in detail the various ash deposition methods, as well as the modifications to inorganic matter's composition that take place during burning. Fuel ash's chemical makeup and fusion behaviour majorly impact the slagging and fouling phenomena.

The biomass used in this research was palm kernel shells (PKS), considering that the potential for PKS in Indonesia is large enough that the supply can be guaranteed. About 32 million tons were produced in Indonesia, or around 46.6% of the whole amount produced worldwide, surpassing every other crude palm oil (CPO) producer with a production of almost 3 million tons. The demand for CPO on the global market is always rising. While this is happening, the growth of Indonesia's palm oil business exhibits a favorable tendency, with yearly growth in production. This indicates that the Indonesian palm oil sector will keep expanding in the future to satisfy the worldwide demand for CPO. As a result, recognizing the potential of waste palm oil to add value to

Indonesia's palm oil industry is crucial (Awalludin et al., 2015). CPO uses fresh fruit bunches (FFB) as its basic material. FFB is processed to create CPO and palm kernel oil (PKO) in a palm oil mill. While FFB was being converted into CPO and PKO, many waste types, including PKS, were produced. The percentage of PKS from the plant is about 5 - 7% (Hambali & Rivai, 2017; Noerrizki et al., 2019; Kurniawan et al., 2020). PKS is the portion of the shell that remains in the palm oil mill after the nut has been crushed. It's a material with fibers, with a brownish-yellow hue, and is simple to manage in large quantities straight from the production line to the final application.

The focus of this research was to reduce the occurrence of slagging and fouling when burning coal and PKS through two-stage PKS washing, namely washing with water followed by washing using glacial acetic acid (CH_3COOH). The washed PKS was then torrefied to improve its calorific value and make it easier to blend with coal as a feedstock for CFPP. This study's primary objective was to lower the amount of ash and alkali oxides that lead to slagging and fouling during blended coal-PKS burning within a boiler or gasifier, considering that information about this is very limited and unclear. Therefore, to understand the impact of coal and washed PKS on ash deposition, the ash fusion temperature (AFT) and its chemical composition were examined.

2. Methods

2.1. Coal characterization

A coal sample originally came from coal mining in Tanjung Enim, South Sumatra, with a sample mark of BBTE. The coal was collected from the stockpiles' surface according to ASTM Standard D 6610-01a: 'Standard Practice for Manually Sampling Coal from the Surfaces of a Stockpile', which provided bulk samples for general laboratory analyses and the estimation of quality and total moisture. This procedure involves manually collecting increments from various locations near the stockpile surface and combining them into one or more bulk samples. Each increment was collected, sealed in plastic-lined canvas bags, and identified. The coal sample was transferred to a coal laboratory for analysis.

The coal sample was crushed and put through a 250- μm sieve (no. 60) in the laboratory so that the analyses could be done on the proximate, ultimate, and calorific values. The proximate analysis was based on ASTM D 3175, and ASTM D 3176. The samples were analyzed close up to find out their inherent moisture (IM), ash (A), and volatile matter (VM). The fixed carbon (FC) content on air dried basis (adb) was calculated as $100\% - (\text{IM} + \text{A} + \text{VM})$. The ultimate analysis included the determination of the carbon and hydrogen contents following ASTM D 3179-89, the nitrogen content based on ASTM D 3179, the total sulfur content by use of the infrared

technique, and the oxygen content calculated at 100% (C + H + N + S + A). In addition, the calorific value (CV) was determined by ASTM standard D 5865-04. The composition of ash chemical analysis was performed using gravimetry for SiO₂, spectrophotometry for TiO₂ and P₂O₅, turbidimetry for SO₃, and atomic absorption spectroscopy for Al₂O₃, Fe₂O₃, CaO, MgO, Na₂O, K₂O, and MnO₂ (Speight, 2005).

2.2. Washing and torrefaction of PKS

The raw PKS samples were obtained from a PKS processing plant that usually supplies PKS to the industry as fuel. PKS samples were washed with water and acetic acid gradually. The stages of this process were as follows:

- A part of raw PKS was sampled and put in a closed container, then torrefied in a furnace that was heated to 450°C for 1 hour and then analyzed for characterization. (sample mark: TRPKS).
- Another part of PKS was washed with water. After washing, the PKS was mixed with water and then heated in a drying oven at 150°C for 1 hour. A part of the washed water PKS was sampled, dried, torrefied, and analyzed for characterization (sample mark: TWPKS).
- Another part of the washed-water PKS was then mixed with glacial acetic acid (CH₃COOH). The variable concentrations of the acid in water were 5%, 10%, and 15%. A volume ratio of PKS and acetic acid of 1:5, then each was heated in a drying oven at 150°C for 1 hour.
- After that, the PKS was filtered and washed again with water until it was relatively acid-free (pH = 7). The washed water and acid PKS were dried and torrefied. The sample marks of the torrefied, washed water and acid are TAPKS-5, TAPKS-10, and TAPKS-15 by using acetic acid concentrations of 5%, 10%, and 15% in water, respectively
- The TAPKS-5, TAPKS-10, and TAPKS-15 were analyzed for characterization.
- Characterization of the above samples, including proximate, ultimate, calorific value, and composition of the ash chemical according to the ASTM standard applied to coal characterization as above (sub-section 2.1). **Figures 1, 2, and 3** show the PKS washing and torrefaction in a furnace, and a block diagram of the washing and torrefaction of the PKS respectively.

2.3. Ash fusion temperature analysis (AFT)

An AFT test was performed to assign the boiler's efficacy and compatibility. The AFT test provides information about how fuel ash behaves as it melts and softens at high boiler temperatures. AFT was measured following ASTM D1857-04, 2013 by viewing through a window in a high-temperature furnace operating in both reduction and oxidation conditions on a molded piece of



Figure 1: PKS washing



Figure 2: PKS torrefaction

coal ash. Cone-shaped ash was heated gradually over 1,000°C to reach a maximum temperature of 1,500°C. These are the temperatures that were recorded under conditions of oxidation or reduction:

- Temperature of initial deformation (IDT): at which the mold's corners start to round.
- Temperature of softening (sphere) (ST): once the mold's top assumes a shape of spherical ($h = w$)
- Temperature of hemisphere (HT): attained when the mold completely assumes a hemisphere-like form ($h = 1/4 w$).
- Temperature of flow (FT): as the ash melts and lands on a furnace floor that has been flattened.

2.4. Slagging and fouling tendencies evaluation

Many indicators have been devised to assess the likelihood of coal and biomass becoming slag and foul based

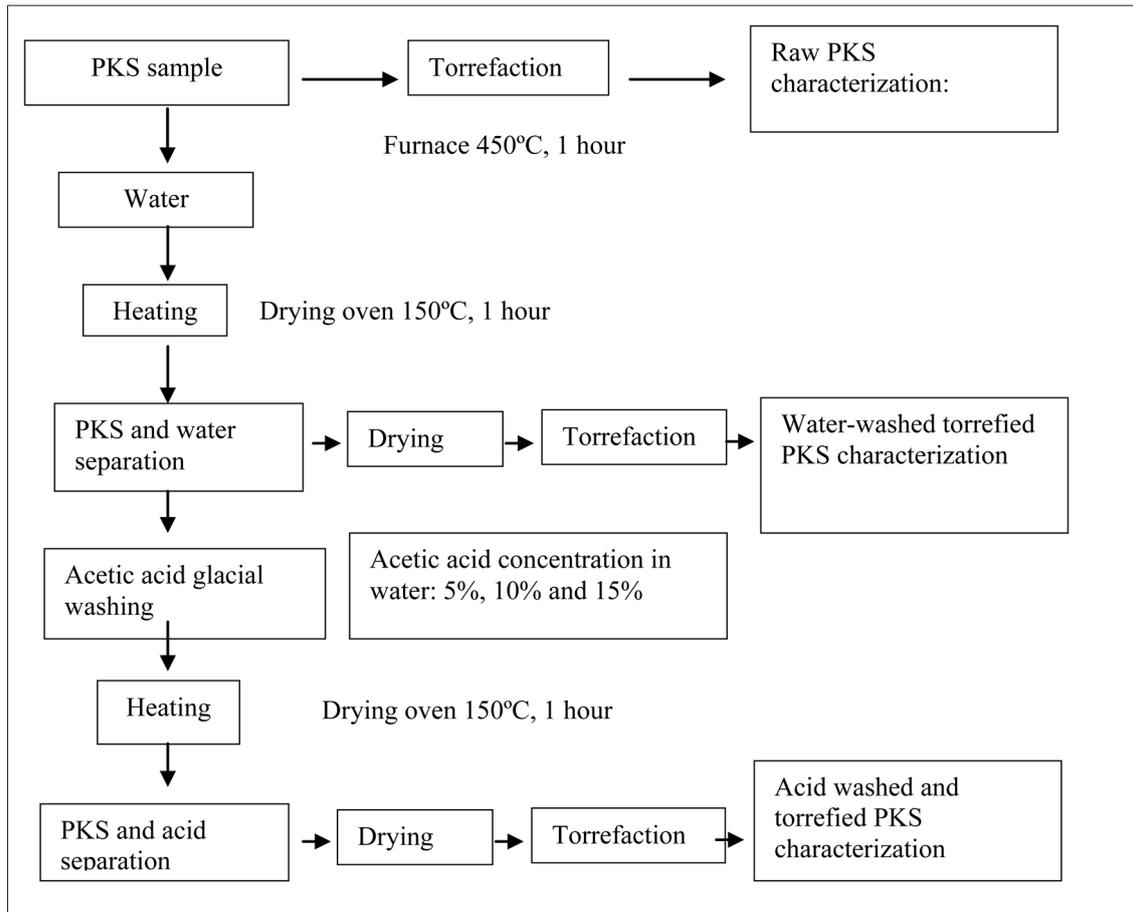


Figure 3: Block diagram of PKS washing and torrefaction

on the chemical composition of the ash. Several indices were calculated based on the ash chemical composition analysis results in mass percent. Reactions resulting in ash fouling and slagging involve elements such as Si, K, Na, S, Cl, P, Ca, Mg, and Fe. Oxides of CaO, K₂O, MgO, Fe₂O₃, and Na₂O are classified as basic compounds, while the SiO₂, Al₂O₃, and TiO₂ oxides are considered acidic compounds. The prediction of the slagging and fouling tendencies are shown in **Equations 1 to 5**.

$$\frac{B}{A} = \frac{(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)}{(SiO_2 + Al_2O_3 + TiO_2)} \quad (1)$$

$$BAI = \frac{Fe_2O_3}{Na_2O + K_2O} \quad (2)$$

$$Fu = \frac{B}{A} \times (Na_2O + K_2O) \quad (3)$$

$$SR = \frac{SiO_2 \times 100}{SiO_2 + Fe_2O_3 + CaO + MgO} \quad (4)$$

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

Slagging hazards depend on the properties of the ash (Zhu et al., 2019). Generally, the slagging tendency increases with the base-to-acid (B/A) ratio. An ash sample has a low slagging tendency when the B/A ratio is < 0.5, a medium slagging tendency for B/A ratios between 0.5 and 0.99, a high slagging tendency for B/A ratios between 1 and 1.74, and a severe slagging tendency for B/A > 1.75 (Kamara et al., 2022). To assess the issues encountered during fluidized bed combustion operations, the bed agglomeration index (BAI) was extended. When the BAI is less than 10, bed agglomeration happens (Lee et al., 2017).

The fouling index (Fu) is determined by the B/A ratio and takes the alkali (Na₂O + K₂O) concentration into account (Yang et al., 2017). Although biomass ash typically contains little sodium, research has indicated that potassium, along with SO₃ and CaO, is one of its main elements in the ash deposits on superheater tubes. One of the main causes of fouling is the increase in surface stickiness that occurs when potassium condenses on fly ash particles (Miles et al., 1996). Fu values below 0.6 are expected to have fouling inclinations, values up to 40 indicate high levels and values over 40 indicate extremely high values. Higher fouling tendencies are correlated with higher Fu levels (Yang et al., 2017). A low fouling propensity is anticipated for Fu < 0.6, a medium fouling

Table 1: Proximate, ultimate, and calorific value of the coal, raw, and torrefied washed biomasses

	IM %	Ash %	VM %	FC %	C %	H %	N %	S %	O %	CV kJ/kg
BBTE	7.08	8.31	39.69	44.92	62.9	5.46	1.05	0.61	21.67	25,711
TRPKS	3.05	5.48	22.50	68.97	73.64	4.00	0.27	0.06	16.56	28,464
TWPKS	3.32	5.11	23.17	68.40	73.6	3.97	0.16	0.06	17.80	28,506
TAPKS-5	1.38	4.95	24.32	69.35	74.26	3.95	0.19	0.06	16.60	28,681
TAPKS-10	1.38	4.80	25.02	68.80	74.39	3.96	0.16	0.05	16.64	28,765
TAPKS-15	1.68	4.32	25.91	68.09	74.62	3.98	0.19	0.05	16.84	28,798

tendency occurs for Fu between 0.6 and 40, and a high fouling tendency occurs for Fu >40.

Rizvi et al. (2015) use the slag viscosity index (SR) to evaluate furnace slag tren. High viscosity values are correlated with low slagging. Low slagging is observed for levels above 72; medium slagging is observed for $65 < Sr < 72$; and high slagging is observed for values below 65. When assessing the slagging potential of fuels, temperature ranges derived from AFT can be applied in addition to the ash chemical composition. When the ST is below 1250°C, there is severe slagging; when the ST is between 1250°C and 1390°C, there is slight slagging; and when the temperature rises over 1390°C, there is slight slagging (**Yu et al., 2014**).

3. Results and Discussion

3.1 Proximate, ultimate, and calorific value analyses

The results of the proximate, ultimate, and calorific values of the raw, torrefied, washed PKS biomass and the coal are shown in **Table 1**. One significant issue with the burning of biomass and coal as fuel is moisture. Fuel combustion is less lucrative with high moisture content due to high transportation expenses as well as the process itself (**Rao et al., 2015**). IM has a substantial impact on the lower CV and is crucial to the combustion process in every fuel for combustion. Fuels with a lot of IM when they burn generate additional exhaust gases, which reduce the combustion temperature (**Mierzwa-Hersztek et al., 2019**). Additionally, because not all flammable components in flue gases will be combusted by the combustion chamber's temperature, the amount of loss resulting from partial and incomplete combustion will rise (**Tsai et al., 2018**).

As can be seen in **Table 1**, after washing, the IM of the TRPKS rises and drops irregularly. This shows that the washing process does not affect the IM content. Differences in grain size likely simply contributed to variations in IM content, causing some to release more easily and others more difficulty throughout the drying process.

Ash-forming components of biomass can be present in the form of salts, bound into the carbon structure (inherent ash), or mixed into the fuel during harvesting or

transportation as mineral particles derived from clay and soil. Since they are spread out evenly among the fuel and can move around with greater ease than the substances in embedded ash, the chemicals in inherent ash are easily flammable and can be used for burning char responses. When the acid concentration rises, the torrefied PKS's ash content decreases.

Under conventional conditions, when the solid fuel is heated without contact with air, the percentage loss in the mass of VM is calculated and adjusted for moisture. One crucial factor that has a big impact on the combustion process is the VM content (**Holtmeyer et al., 2013**). The VM content of PKS was relatively low. After washing, the VM increased slightly, and as a result, the FC decreased and increased irregularly. After biomass was heated and VM was released, the solid combustible residue (FC) remained, excluding the moisture content and ash (**Brewer et al., 2014**). Any material's FC serves as the primary heat generator during burning and provides an approximation of the fuel's heating value. CV will rise in response to an increase in the proportion of FC in coal (**Anshariah et al., 2020**).

One of the most significant thermophysical characteristics defining a material's energy potential is its CV. This criterion serves as the foundation for evaluating fuel's usefulness as a source of energy. Moisture and the chemical composition of the fuel have a significant impact on CV. The coal that was utilized in this study has a comparatively high CV. At 25,711 kJ/kg, the coal is classified as the medium-calorific coal category. While the CV of the torrefied PKS ranges from 28,464 to 28,798 kJ/kg. The CV of torrefied washed PKS increased by increasing the acid concentration.

To assess how washing affects the degree of de-ashing (DDA) and the degree of CV improvement (DCI), the evaluation is calculated based on **Equations 6** and **7**. The results can be seen in **Table 2**. Raising the acid con-

Table 2: DDA and DCI of the washed PKS

	DDA, %	DCI, %
TWPKS	6.75	0.15
TAPKS-5	9.67	0.76
TAPKS-10	12.41	1.06
TAPKS-15	21.17	1.18

Table 3: Coal and torrefied PKS ash chemical composition (mass %)

	BBTE	TRPKS	TWPKS	TAPKS-5	TAPKS-10	TAPKS-15
SiO ₂	45.9	69.2	75.6	76.35	77.85	79.75
Al ₂ O ₃	23.11	3.30	3.96	5.94	3.83	3.26
Fe ₂ O ₃	9.55	3.65	3.66	3.78	2.89	2.43
K ₂ O	2.11	7.49	5.10	3.16	3.91	4.19
Na ₂ O	0.83	0.98	0.96	1.06	1.07	0.74
CaO	6.45	4.83	3.70	3.24	2.93	2.24
MgO	2.49	3.52	2.74	2.03	2.00	1.96
MnO	0.037	0.22	0.21	0.13	0.12	0.12
TiO ₂	0.74	0.22	0.17	0.42	0.18	0.14
P ₂ O ₅	0.53	4.92	3.14	2.55	3.02	3.32
H ₂ O	0.2	0.08	0.03	0.05	0.02	0.06
SO ₃	5.34	0.97	0.34	0.15	0.64	0.64

Table 4: Slagging and fouling tendencies indices

	BBTE	TRPKS	TWPKS	TAPKS-5	TAPKS-10	TAPKS-15
B/A	0.31	0.28	0.20	0.16	0.16	0.14
BAI	3.25	0.43	0.60	0.90	0.58	0.49
Fu	0.90	2.38	1.23	0.68	0.78	0.69
SR	71.28	85.22	88.21	89.40	90.87	92.32
Rs	0.19	0.01	0.01	0.01	0.01	0.01

Table 5: Blended coal and washed torrefied PKS characteristics

	BBTE (C)	TAPKS-5	C-TAPKS 95:5	C-TAPKS 90:10	C-TAPKS 85:15	C-TAPKS 80:20	C-TAPKS 75:25
Ash, %	8.31	4.95	8.14	7.97	7.81	7.64	7.47
CV, kcal/kg	25,711	28,681	25,860	26,008	26,157	26,305	26,454
SiO ₂ , %	45.9	76.35	47.42	48.95	50.47	51.99	53.51
Al ₂ O ₃ , %	23.11	5.94	22.25	21.39	20.53	19.68	18.82
Fe ₂ O ₃ , %	9.55	3.78	9.26	8.97	8.68	8.40	8.11
K ₂ O, %	2.11	3.16	2.16	2.22	2.27	2.32	2.37
Na ₂ O, %	0.83	1.06	0.84	0.85	0.86	0.88	0.89
CaO, %	6.45	3.24	6.29	6.13	5.97	5.81	5.65
MgO, %	2.49	2.03	2.47	2.44	2.42	2.40	2.38
TiO ₂ , %	0.74	0.42	0.72	0.71	0.69	0.68	0.66
B/A	0.31	0.16	0.30	0.29	0.29	0.28	0.27
Fu	0.90	0.68	0.89	0.88	0.87	0.86	0.85
Rs	0.19	0.01	0.18	0.17	0.16	0.15	0.14

Table 6: Ash fusion temperature of the blended coal-torrefied washed biomass (°C)

Sample mark	Reducing				Oxidizing			
	IDT	ST	HT	FT	IDT	ST	HT	FT
C-TAPKS 95:5	1,187	1,212	1,346	1,304	1,273	1,327	1,337	1,377
C-TAPKS 90:10	1,174	1,202	1,248	1,299	1,265	1,315	1,341	1,360
C-TAPKS 85:15	1,159	1,195	1,269	1,285	1,238	1,261	1,298	1,321
C-TAPKS 80:20	1,150	1,194	1,266	1,285	1,236	1,281	1,320	1,353
C-TAPKS 75:25	1,147	1,182	1,251	1,266	1,238	1,257	1,296	1,341

tent increased the DDA and DCI of the torrefied and washed PKS.

$$DDA = \frac{Ash_i - Ash_f}{Ash_i} \times 100\% \quad (6)$$

$$DCI = \frac{CV_f - CV_i}{CV_i} \times 100\% \quad (7)$$

where:

Ash_i : the initial ash content

Ash_f : the final ash content

CV_i : the initial CV

CV_f : the final CV

The ultimate analysis, as shown in **Table 1**, was mostly concerned with C, H, N, O, and total S content. These are the principal constituents of burning biomass and assess the fuel's effectiveness and possible pollutant behaviour (**Lomeda-De Mesa et al., 2020**). The relative amounts of C, H, and O in biomass indicate its calorific value (**Tripathi et al., 2016**). The C content in biomass is directly correlated to CV. The greater the amount of C, the more heat will be produced (**Miranda et al., 2015; Z. Liu et al., 2014**). The C content increased linearly due to the increase in CV. PKS sulfur content is very low, so the washing process has no effect. Since it does not create acid rain and GHG emissions, biomass with a low sulfur content is more environmentally benign when burned. In general, torrefied PKS samples that were washed with glacial acetic acid have better characteristics compared to raw torrefied PKS that were not washed and that were only washed with water.

3.2. Evaluation of slagging and fouling tendencies

Slagging and fouling tendencies during coal and biomass combustion in boilers could be predicted based on the chemical composition of ash. The ash chemical composition analysis of the coal and torrefied PKS in mass % is shown in **Table 3**. It has been demonstrated that while basic compounds have the opposite effect, acidic substances raise the melting temperature overall (**Lachman et al., 2021**).

Table 3 shows that the torrefied raw PKS has a high silica oxide (SiO_2) content, which rises with an increasing acid concentration. It is acknowledged that the most common inorganic substance found in biomass is SiO_2 . This is explicable by the fact that silica, one of the most prevalent elements in the Earth's crust, primarily transfers to plants as water-soluble H_4SiO_4 during botanical growth (**Chen et al., 2022**).

Alkali metals, such as Na and K, have a substantial effect on the process of slagging biomass ash. These two substances tend to evaporate inside the gasifier/combustor at high temperatures. Following a sequence of events, they condense as submicron ash particles, which subsequently form a sticky film and adhere to the heating surface (**Alam et al., 2023**). The raw torrefied PKS has a

high K_2O content of 7.49% and decreases to 3.16% after washing with 5% acid. Since potassium is mostly found in living biomass as free K^+ ions and is therefore highly mobile, there was a decrease in K_2O . These ions precipitate as potassium salts that are inorganic and readily soluble in water, such as KCl and KNO_3 (**Clery et al., 2018**). The Na_2O of the raw torrefied PKS was 0.98% and decreased to 0.74% after washing with the 15% acid. Other oxides, such as Al_2O_3 , Fe_2O_3 , CaO, MgO, and TiO_2 , were often lowered as a result of acid or water washing. The tendency of slagging, fouling, and other factors influencing ash deposition during combustion in the boiler of coal, raw, and washed torrefied PKS is shown in **Table 4**.

The criterion for slagging and fouling in every sample shows low slagging and medium fouling propensities. Every sample has $B/A < 0.5$, $BAI < 10$, $SR > 70$, and $Rs < 0.5$. While the fouling tendency is categorized as medium (between 0.6 and 40).

3.3. Blended coal and torrefied biomass

According to the ash content and CV results, including the tendency for slagging and fouling, washing PKS with 5% acid has given a good result. Therefore, mixing coal and PKS is done using PKS that has been washed with water and 5% acid. The characteristics of the blended coal and torrefied biomass at the weight % ratio, are shown in **Table 5**.

The washed-torrefied PKS has better characteristics than the coal used in this study. By blending them at some weight ratio, the blended coal-PKS has better characteristics than coal alone. Lower ash content, higher CV, lower B/A ratio, Fu, and Rs at all of the ratios. Based on the fouling index, the blended coals and washed-torrefied PKS of such composition have a medium tendency of fouling (0.6-40) and a low tendency of slagging (<0.6). The AFT of the blended coal and washed-torrefied PKS at reducing and oxidation conditions in °C is shown in **Table 6**.

All of the blended coals have a strong propensity for fouling and slagging, with the ST below 1,250°C, while in oxidizing conditions they have slight slagging (medium), with the ST between 1250°C and 1390°C. These results were a little bit different than the results according to the chemical composition of the ash.

4. Conclusions

Washing PKS in two stages with water and glacial acetic acid, followed by a torrefaction process at a temperature of 450°C for 1 hour, was successful in raising the calorific value and lowering the ash content. Among the three factors affecting the acid concentration in the water under tests 5, 10, and 15%, the higher the acetic acid concentration, the lower the ash content and the higher the CV. The results of the analysis of the ash

chemical composition show that basic oxides such as K_2O , N_2O , MgO , and CaO decrease, so the possibility of slagging and fouling also decreases. According to the results of the ash chemical composition analysis, blended coal with torrefied PKS that has been washed with 5% acid in several comparisons between coal and PKS tends to have low slagging and medium fouling. Based on AFT, reduction conditions tend to have high levels of slagging and fouling, while in oxidation conditions the tendency is medium.

Acknowledgement

The authors gratefully acknowledge the Head of Renewable Energy Program Houses, Energy and Manufacture Organization Research, The Agency of National Research and Innovation who have funded this research, and the Head of the Mining Technology Research Centre, The Agency of National Research and Innovation who has supported and encouraged this research, and all colleagues involved in this activity.

5. References

- Alam, T., Hoadley, A., Dai, B., & Zhang, L. (2023): Impact of potassium on bio-ash slagging and resultant slag flowing characteristics under mild reducing environment. *Fuel Processing Technology*, 243, 107672. <https://doi.org/10.1016/j.fuproc.2023.107672>
- Anshariah, Imran, A., Widodo, S., & Irvan, U. R. (2020): Correlation of fixed carbon content and calorific value of South Sulawesi Coal, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 473(1), 012106. <https://doi.org/10.1088/1755-1315/473/1/012106>
- Awalludin, M. F., Sulaiman, O., Hashim, R., & Nadhari, W. N. A. W. (2015): An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction. *Renewable and Sustainable Energy Reviews*, 50, 1469–1484. <https://doi.org/10.1016/j.rser.2015.05.085>
- Brewer, C. E., Chuang, V. J., Masiello, C. A., Gonnermann, H., Gao, X., Dugan, B., Driver, L. E., Panzacchi, P., Zygorakis, K., & Davies, C. A. (2014): New approaches to measuring biochar density and porosity. *Biomass and Bioenergy*, 66, 176–185. <https://doi.org/10.1016/j.biombioe.2014.03.059>
- Chen, K., Ng, K. H., Cheng, C. K., Cheng, Y. W., Chong, C. C., Vo, D.-V. N., Witoon, T., & Ismail, M. H. (2022). Biomass-derived carbon-based and silica-based materials for catalytic and adsorptive applications- An update since 2010. *Chemosphere*, 287, 132222. <https://doi.org/10.1016/j.chemosphere.2021.132222>
- Clery, D. S., Mason, P. E., Rayner, C. M., & Jones, J. M. (2018): The effects of an additive on the release of potassium in biomass combustion. *Fuel*, 214, 647–655. <https://doi.org/10.1016/j.fuel.2017.11.040>
- Hambali, E., & Rivai, M. (2017): The Potential of Palm Oil Waste Biomass in Indonesia in 2020 and 2030. *IOP Conference Series: Earth and Environmental Science*, 65, 012050. <https://doi.org/10.1088/1755-1315/65/1/012050>
- Holtmeyer, M. L., Li, G., Kumfer, B. M., Li, S., & Axelbaum, R. L. (2013). The Impact of Biomass Cofiring on Volatile Flame Length. *Energy & Fuels*, 27(12), 7762–7771. <https://doi.org/10.1021/ef4013505>
- Indonesia. (2021): *Indonesia - High-level Segment Statement COP 26*.
- Kamara, B., Kallon, D. V. Von, & Mashinini, P. M. (2022). Fouling and Slagging Investigation on Ash Derived from Sasol Coal Using ICP and XRF Analytical Techniques. *Applied Sciences*, 12(22), 11560. <https://doi.org/10.3390/app122211560>
- Kleinhans, U., Wieland, C., Frandsen, F. J., & Spliethoff, H. (2018): Ash formation and deposition in coal and biomass fired combustion systems: Progress and challenges in the field of ash particle sticking and rebound behavior. *Progress in Energy and Combustion Science*, 68, 65–168. <https://doi.org/10.1016/j.peccs.2018.02.001>
- Kurniawan, M. P., Guritno, A. D., Purwantana, B., & Suparsono, W. (2020): Production cost approach and material flow cost accounting as a step towards increasing responsibility, efficiency, and sustainability (RES): the case of palm oil mill in Banten Indonesia. *IOP Conference Series: Earth and Environmental Science*, 425(1), 012042. <https://doi.org/10.1088/1755-1315/425/1/012042>
- Lachman, J., Baláš, M., Lisý, M., Lisá, H., Milčák, P., & Elbl, P. (2021): An overview of slagging and fouling indicators and their applicability to biomass fuels. *Fuel Processing Technology*, 217, 106804. <https://doi.org/10.1016/j.fuproc.2021.106804>
- Lee, Y., Kim, J., Kim, D., & Lee, Y. (2017): Experimental Study of Co-firing and Emission Characteristics Fueled by Sewage Sludge and Wood Pellet in Bubbling Fluidized Bed. *Clean Technology*, 23(1), 80–89. <https://doi.org/10.7464/ksct.2017.23.1.080>
- Liu, Q., Zhong, W., Zhou, J., & Yu, Z. (2022): Effects of S and Al on K Migration and Transformation during Coal and Biomass Co-combustion. *ACS Omega*, 7(18), 15880–15891. <https://doi.org/10.1021/acsomega.2c00994>
- Liu, Z., Fei, B., Jiang, Z., Cai, Z., & Liu, X. (2014): Important properties of bamboo pellets to be used as commercial solid fuel in China. *Wood Science and Technology*, 48(5), 903–917. <https://doi.org/10.1007/s00226-014-0648-x>
- Lomeda-De Mesa, R. A. P., Soriano, A. N., Marquez, A. R. D., & Adornado, A. P. (2020): Study on the proximate and ultimate analyses and calorific value of coal blending between torrefied biomass from coconut (*Cocos nucifera*) husk and Semirara coal. *IOP Conference Series: Earth and Environmental Science*, 471(1), 012004. <https://doi.org/10.1088/1755-1315/471/1/012004>
- Lupiáñez, C., Mayoral, M. C., Guedea, I., Espatolero, S., Díez, L. I., Laguarda, S., & Andrés, J. M. (2016): Effect of cofiring on emissions and deposition during fluidized bed oxy-combustion. *Fuel*, 184, 261–268. <https://doi.org/10.1016/j.fuel.2016.07.027>
- Mierzwa-Hersztek, M., Gondek, K., Jewiarz, M., & Dziedzic, K. (2019): Assessment of energy parameters of biomass and biochars, leachability of heavy metals and phytotoxic-

- ity of their ashes. *Journal of Material Cycles and Waste Management*, 21(4), 786–800. <https://doi.org/10.1007/s10163-019-00832-6>
- Miles, T. R., Miles, T. R., Baxter, L. L., Bryers, R. W., Jenkins, B. M., & Oden, L. L. (1996): Boiler deposits from firing biomass fuels. *Biomass and Bioenergy*, 10(2–3), 125–138. [https://doi.org/10.1016/0961-9534\(95\)00067-4](https://doi.org/10.1016/0961-9534(95)00067-4)
- Miranda, T., Montero, I., Sepúlveda, F., Arranz, J., Rojas, C., & Nogales, S. (2015): A Review of Pellets from Different Sources. *Materials*, 8(4), 1413–1427. <https://doi.org/10.3390/ma8041413>
- Mlonka-Mędrala, A., Magdziarz, A., Dziok, T., Sieradzka, M., & Nowak, W. (2019): Laboratory studies on the influence of biomass particle size on pyrolysis and combustion using TG GC/MS. *Fuel*, 252, 635–645. <https://doi.org/10.1016/j.fuel.2019.04.091>
- Noerizki, A. M., Putri, T. K., & Ernah, E. (2019): Utilization of palm oil waste as bioenergy. *Sustinere: Journal of Environment and Sustainability*, 3(1), 48–66. <https://doi.org/10.22515/sustinere.jes.v3i1.77>
- Nonaka, M., Hirajima, T., & Sasaki, K. (2011): Upgrading of low rank coal and woody biomass mixture by hydrothermal treatment. *Fuel*, 90(8), 2578–2584. <https://doi.org/10.1016/j.fuel.2011.03.028>
- Rao, Z., Zhao, Y., Huang, C., Duan, C., & He, J. (2015): Recent developments in drying and dewatering for low rank coals. *Progress in Energy and Combustion Science*, 46, 1–11. <https://doi.org/10.1016/j.pecs.2014.09.001>
- Rizvi, T., Xing, P., Pourkashanian, M., Darvell, L. I., Jones, J. M., & Nimmo, W. (2015): Prediction of biomass ash fusion behaviour by the use of detailed characterisation methods coupled with thermodynamic analysis. *Fuel*, 141, 275–284. <https://doi.org/10.1016/j.fuel.2014.10.021>
- Speight, J. G. (2005): *Handbook of Coal Analysis*. Wiley. <https://doi.org/10.1002/0471718513>
- Teixeira, P., Lopes, H., Gulyurtlu, I., Lapa, N., & Abelha, P. (2012). Evaluation of slagging and fouling tendency during biomass co-firing with coal in a fluidized bed. *Biomass and Bioenergy*, 39, 192–203. <https://doi.org/10.1016/j.biombioe.2012.01.010>
- Teixeira, P., Lopes, H., Gulyurtlu, I., Lapa, N., & Abelha, P. (2014): Slagging and Fouling during Coal and Biomass Cofiring: Chemical Equilibrium Model Applied to FBC. *Energy & Fuels*, 28(1), 697–713. <https://doi.org/10.1021/ef4018114>
- Tortosa-Masiá, A., Ahnert, F., Spliethoff, H., Loux, C., & Hein, K. (2005). Slagging and fouling in biomass co-combustion. *Thermal Science*, 9(3), 85–98. <https://doi.org/10.2298/TSCI0503085T>
- Tripathi, M., Sahu, J. N., & Ganesan, P. (2016): Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews*, 55, 467–481. <https://doi.org/10.1016/j.rser.2015.10.122>
- Tsai, Y.-T., Yang, Y., Wang, C., Shu, C.-M., & Deng, J. (2018): Comparison of the inhibition mechanisms of five types of inhibitors on spontaneous coal combustion. *International Journal of Energy Research*, 42(3), 1158–1171. <https://doi.org/10.1002/er.3915>
- Umar, D. F., & Rohayati, T. (2021). Study on chemical characteristics of coal and biomass blend and the tendency of its ash deposition. *Indonesian Mining Journal*, 24(2), 113–126. <https://doi.org/10.30556/imj.Vol24.No2.2021.1242>
- Wibisono, S. A., Dwitama, E. P., & Prahesti, I. O. (2019): Petrography and Coal Geochemistry In Pahirangan And Surrounding Area, Kotawaringin Timur District, Central Kalimantan Province (In Indonesian). *Geological Resources Bulletin*, 14(1), 65–78. <https://doi.org/10.47599/bsdg.v14i1.245>
- Yang, X., Ingham, D., Ma, L., Srinivasan, N., & Pourkashanian, M. (2017): Ash deposition propensity of coals/blends combustion in boilers: a modeling analysis based on multi-slagging routes. *Proceedings of the Combustion Institute*, 36(3), 3341–3350. <https://doi.org/10.1016/j.proci.2016.06.060>
- Yao, X., Xu, K., Yan, F., & Liang, Y. (2017): The Influence of Ashing Temperature on Ash Fouling and Slagging Characteristics during Combustion of Biomass Fuels. *BioResources*, 12(1). <https://doi.org/10.15376/biores.12.1.1593-1610>
- Yu, L. Y., Wang, L. W., & Li, P. S. (2014): Study on prediction models of biomass ash softening temperature based on ash composition. *Journal of the Energy Institute*, 87(3), 215–219. <https://doi.org/10.1016/j.joei.2014.03.011>
- Zhu, C., Tu, H., Bai, Y., Ma, D., & Zhao, Y. (2019): Evaluation of slagging and fouling characteristics during Zhundong coal co-firing with a Si/Al dominated low rank coal. *Fuel*, 254, 115730. <https://doi.org/10.1016/j.fuel.2019.115730>

SAŽETAK

Dvostupanjsko pranje ljuske palmine koštice vodom i octenom kiselinom kao priprema sustava za suspaljivanje s ugljenom

Ljuske palminih jezgri (PKS) postupno su isprane vodom i ledenom octenom kiselinom (CH_3COOH) kako bi se pripremile za suspaljivanje s ugljenom. Zatim su toreficirane na $450\text{ }^\circ\text{C}$ jedan sat. Pranje je obavljeno kako bi se smanjila koncentracija pepela i alkalnih oksida, što bi smanjilo mogućnost stvaranja troske i obraslina. Istraživanje je provedeno s obzirom na to da su informacije o ispiranju PKS-a octenom kiselinom i njihovu toreficiranju vrlo ograničene i nejasne. Rezultati su pokazali da isprani i toreficirani PKS ima bolja svojstva od sirovoga PKS-a ili onoga ispranog vodom. Mješavina ugljena s PKS-om ispranim kiselinom i toreficiranim ima nisku šljaku i srednju tendenciju obraštanja. Međutim, na temelju temperature taljenja pepela, sklonost stvaranju šljake i obraslina visoka je u redukcijskim uvjetima i srednja u uvjetima oksidacije.

Ključne riječi:

pranje, torefikacija, šljaka, obraslina, temperatura taljenja pepela

Authors' contribution

Datin Fatia Umar (1), Professor Research, Ph.D., Chemical Science and Engineering, provided the idea and methodology, conceptualization, visualization of the data, interpretations, and presentation of the results, research management, and writing, reviewing, and editing the paper. **Zulfahmi, Zulfahmi** (2), Researcher, Ph.D., Geological Engineering, performed the fieldwork, contributing to conceptualization, visualization of the data, interpretations, and presentation of the results, writing and editing the paper. **Suganal, Suganal** (3), Researcher, Bachelor, Chemical Engineering, performed the fieldwork, visualization of the data, interpretations, and presentation of the results and reviewed the paper. **Nendaryono Madiutomo** (4), Researcher, Magister, Geological Engineering, performed the fieldwork, visualization of the data, and reviewed the paper. **Truman Wijaya** (5), Researcher, Bachelor, Geological Engineering, performed the fieldwork, visualization of the data, and reviewed the paper. **Miftahul Huda** (6), Researcher, Ph.D., Mining Engineering, performed the fieldwork, contributing to conceptualization, visualization of the data, interpretations and presentation of the results, and writing and editing the paper. **Liston Setiawan** (7), Researcher, Bachelor, Mining Engineering, performed the fieldwork, visualization of the data, and reviewed the paper. **Edwin Akhdiat Daranin** (8), Researcher, Magister, Geological Engineering, performed the fieldwork, visualization of the data, interpretations, and presentation of the results, and reviewed the paper. **Gunawan, Gunawan** (9), Researcher, Bachelor, Mining Engineering, performed the fieldwork, and visualization of the data. **Ika Monika** (10), Researcher, Bachelor, Applied Chemistry, performed the fieldwork and visualization of the data.