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Impact of pre-treatment for coconut husk by water leaching on fuel and ash characteristics during combustion in a fluidized bed reactor

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Abstract

This study investigated the impact of water leaching of a coconut husk on improving fuel characteristics and preventing bed agglomeration in fluidized bed combustion. The leaching process was conducted in a laboratory-scale setup at water flow rates of 150 ml/min and 250 ml/min, and electrical conductivity (EC) was used to determine the optimum leaching duration. Potassium oxide decreased by up to 40%, chlorine by up to 82%, and ash content practically halved, reaching as low as 2.98% in the best case, as a result of the treatment. Importantly, the fuel's heating value stayed around 20.5 MJ/kg. Physically, the leached husk exhibited a larger surface area and increased pore volume, corresponding to a rise in volatile matter from 65% to nearly 70%. During combustion tests at 800 °C, the treated coconut husk remained fluidized for much longer, up to 93 minutes, compared to just 32 minutes for the untreated fuel, indicating a strong reduction in bed agglomeration. The details of microscopic analysis revealed that leaching promoted the formation of compounds with higher melting points, thereby preventing the formation of low-melting-point potassium silicates that cause agglomeration. The FactSage program (version 8.2) was used for thermochemical modeling based on the ash composition, and the simulation results confirmed that the ash melting temperature increased from below 900 °C to above 1,300 °C after leaching. These results demonstrate that simple water leaching can effectively enhance the quality of coconut husk fuel and help prevent operational issues in fluidized bed combustors.

Keywords: Agglomeration, Coconut husk, Combustion, FactSage, Water leaching

1. Introduction

Energy is one of the primary resources utilized in the industrial sector. In 2025, Thailand's final energy consumption was 84,713 ktoe, with fossil fuels accounting for 84.9% [1]. Excessive use of fossil fuels has consequences for energy security, sustainability, and the environment. Using biomass as an alternative energy source helps reduce dependence on fossil fuels, increases energy security, and reduces environmental impacts. Shell, husk, and leaf stalks are the three categories of waste and residue generated during the processing of coconuts into food products in Thailand. The shell and husk are considered residues and can be used as alternative fuel and growing media, respectively. As for the leaf stalks, they are considered waste and await disposal. The husk totals 147.9 ktoe, with the remainder located in the central region (85.1 ktoe) [2]. This suggests that the husk from coconut processing has strong potential as an alternative energy source.

Fluidized bed technology has seen increasing application in combustion processes, particularly for coal and biomass co-combustion, which is widely used in the industrial sector, due to its good mixing and efficient heat

transfer properties. Silica sand (SiO_2) is generally used as the bed material in both bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) reactors. In fluidized bed boilers, ash-related problems such as slagging, bed agglomeration, and fouling result in deposits that impair fluidization and heat transfer, leading to unsteady temperatures, defluidization, and unexpected shutdowns. These problems reduce plant efficiency and increase cleaning and maintenance costs. Potassium and sodium are typical alkali metals that interact with silica to form low-melting-point compounds such as potassium silicate ($K_2O{\cdot}4SiO_2$), which has a melting point of about 750°C [3]. This promotes slagging and agglomeration. Deposition on convective heat transfer surfaces, such as heat exchanger tubes, is known as fouling. Alkali metals react with sulfur dioxide and chlorine in the flue gas when heated, forming sulfates and chlorides that vaporize and condense on heat-exchange equipment, generating sticky substances that reduce heat-exchange efficiency.

Biomass fuels, however, often contain substantial quantities of alkali metals (notably potassium and sodium), chlorine, sulfur, and silica, which present operational challenges such as slagging, bed agglomeration, and fouling during combustion [3-5]. For instance, Elled et al. [4] reported that potassium-rich biomass ash can cause bed agglomeration through the formation of low-melting potassium silicates with eutectic temperatures near 754 °C. Similarly, Morris et al. [5] found that elevated potassium and chlorine concentrations in biomass ashes result in severe fouling and slagging in fluidized beds, thereby reducing operational stability. Deng et al. [6] demonstrated that potassium and sodium oxides react readily with bed silica to form alkali silicates and aluminates, which lower ash melting temperatures to below 800 °C and accelerate deposit formation. Chlorine further intensifies corrosion by generating volatile alkali chlorides and releasing HCl, which increases maintenance costs [7]. Additionally, sulfur can alter ash behavior by forming sulfates that affect melting characteristics and deposit adhesion [8, 9]. The findings from these studies highlight the importance of controlling key elements in biomass fuels, such as K, Na, Cl, and S, to reduce slagging, fouling, and agglomeration in fluidized-bed combustion systems.

Numerous studies have investigated the improvement of biomass quality through leaching. Generally, biomass composition contains relatively high levels of alkali metals (K, Na), as well as Cl and ash. These components result in compounds with low melting temperatures, leading to agglomeration [4, 5] and fouling [6, 10] problems. The leaching process depends on various parameters, such as fuel elemental composition, solid-to-liquid ratio, leaching methods, and leaching medium, which affect the efficiency of reducing K, Na, Cl, and ash content. Fuel that has undergone leaching can effectively reduce problems when used as fuel. There have been research studies on improving biomass quality by reducing potassium content using water as a leaching agent [6-9, 11]. Water as a leaching agent offers several advantages, including economic efficiency, the absence of residual chemicals, and operator safety. These studies demonstrated that potassium levels in biomass could be reduced by 24% to 87%, and ash content by 15% to 56%.

Leached biomass additionally helps reduce ash-related issues and improves the combustion process. According to the study by Ravichandran and Corscadden [12], the four different types of biomass: barley, reed, switch, and wheat were leached by water, and burned in a stove, this was discovered that the fuel that had been leached also made combustion easier, which led to a higher conversion of CO to CO_2 and a higher combustion efficiency because the leached biomass had more volatiles compared to non-leached fuels. However, previous works [6-9, 11] still examine the effects of ash from fluidized bed combustion on the leaching of potassium and chlorine, and on ash concentration, in coconut husk, a biomass fuel with potential as an energy source in Thailand.

This study aims to examine the combustion behavior of ash from fuel derived from coconut husk that has been quality-improved by washing with water at different flow rates, compared with fuel that has not been washed. The combustion experiments were carried out in a bubbling fluidized bed reactor with heaters to maintain a temperature of 800 °C. The chemical composition of the bed particles that were obtained during combustion testing was examined. Additionally, the FactSage program (version 8.2) was used to estimate the melting temperature of the ash, following previous work [13].

2. Materials and methods

2.1 Laboratory Water-leaching System

Coconut husk was shredded using agricultural machinery. The collected samples, sized to a width of 1–11 mm and a length of 3-16 cm, were processed in a water-leaching system at the laboratory scale. The schematic diagram of the leaching system is shown in Figure 1. The leaching system consisted of a PVC reactor tube with an internal diameter of 52 mm and a height of 1.2 m, capable of holding 100 g of coconut husk per run. Tap water, typically at about 32 °C, was supplied to the bottom of the reactor tube by a peristaltic pump, and during the experiments, the flow rate was adjusted to 150 ml/min and 250 ml/min. The leachate exited from the top of the reactor tube, where its electrical conductivity (EC) was measured.

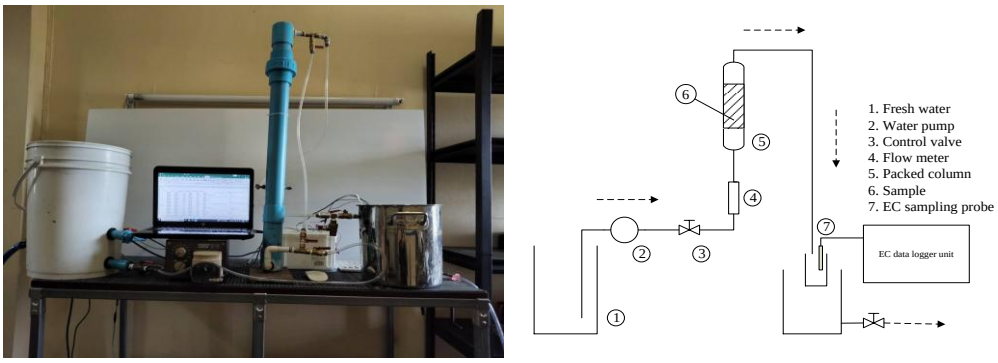


Figure 1 Schematic diagram of the leaching system.

This study therefore investigated the effects of water flow rate on the leaching of alkali metals, such as potassium, and on ash content. Electrical conductivity can serve as an indicator of concentration and is directly proportional to water-soluble elemental components such as potassium, sodium, magnesium, phosphorus, sulfur, and Cl, as demonstrated in the studies of Schmidt et al. [14] and Peiris and Gunarathne [15], which examined biomass leaching by soaking and measured the electrical conductivity of the leachate. In this research, the EC of water leached from coconut husk was measured using an online sensor, which had an error of 1.42% compared with the standard solution of 1,413 µS/cm [16]. The EC was recorded every 12 seconds until the water reached 300 µS/cm (±10 µS/cm), which corresponds to typical tap water with an EC in the range of 300-350 µS/cm. The water-leaching experiment was then stopped, and the samples were taken out of the reactor, dried, and prepared for the ash's elemental composition analysis.

2.2 Combustion Test System

A laboratory-scale fluidized bed reactor (as shown in Figure 2) was used to test samples of coconut husk and samples treated with water to improve their quality. The fluidized bed reactor is made of stainless steel 316 and is cylindrical, with an internal diameter of 9 cm and a height of 1.8 m. The reactor's bottom is equipped with an air distributor plate with 85 holes, each 0.6 mm in diameter. The silica sand was used as a bed material and filled to a bed particle height-to-reactor diameter ratio of 0.5 (Hb/Db), which corresponds to a bed particle height of 4.5 cm. Two K-type thermocouples are installed at the mid-height and bottom of the bed layer (as shown in Figure 2, position 4). The pressure transmitters were installed in the bed material area to measure the pressure drop during combustion. Temperature and pressure drop data are recorded by a data logger (DT505) every 2 seconds.

In the combustion test, the fuel feed rate 0.6 g/min, the excess air rate (set at 50%), and the combustion temperature (controlled by a heater) were kept constant at 800 °C for all experiments. The bed particle velocity was set at a ratio of U/Umf = 3, where the minimum velocity (Umf) is 0.04859 m/s (bed particle size 287 µm, 800°C, particle density 3,230 kg/m³).

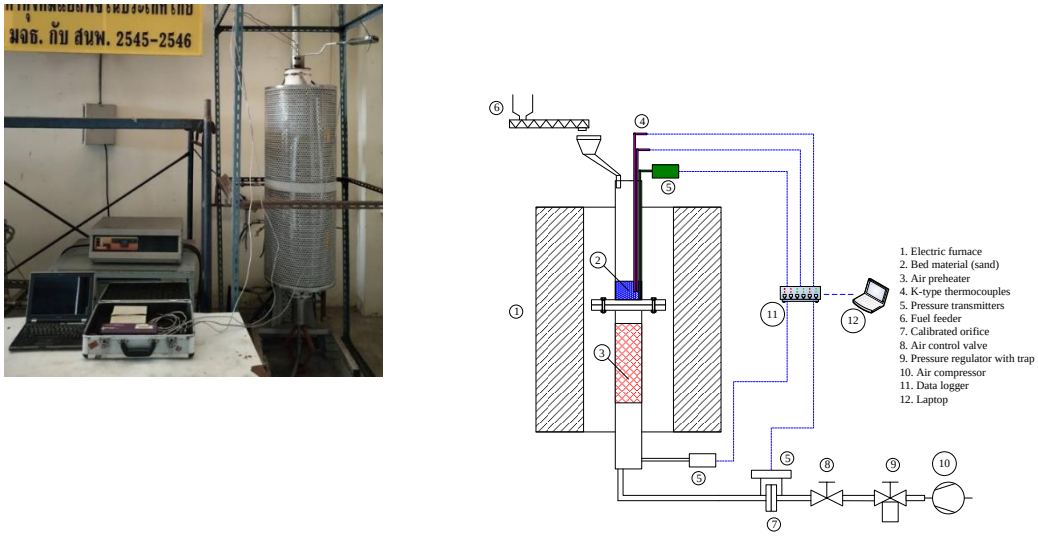


Figure 2 Fluidized bed combustor schematic diagram.

2.3 Experimental Procedure

The experiments were performed during the leaching process and the combustion in a fluidized bed combustor, which were divided into 4 main steps.

Step 1: Analysis of sample properties: the chemical and physical properties of the coconut husk sample were examined using both proximate and ultimate analyses to identify elemental composition and physical properties, including moisture, fixed carbon, ash, and heating value. The chemical composition of coconut husk ash was examined using X-ray fluorescence (XRF). Ash, analyzed by XRF, was prepared in accordance with ASTM E1755-01. The ash samples with a particle size of 425 μm is weighed to 2 grams and placed in a furnace at 550 °C for 4 h to ensure that carbon is eliminated. After that, cool down in a desiccator for 30 mins.

Step 2: Testing biomass quality improvement by water leaching; coconut husk that was chopped into fiber was placed in a reactor for leaching (as described in section 2.1), with 100 grams used in each experiment. To study the dependent variables, namely physical and chemical properties, the water flow rate was adjusted to 150 ml/min and 250 ml/min. Additionally, the experiment examined different leaching times by maintaining a constant flow rate of 150 ml/min and stopping the washing experiment when the EC reached approximately 300 μS/cm and 700 μS/cm. In addition, water-leached samples were analyzed for surface area and porosity using the physisorption method, and the results were compared with those for non-leached fuel to observe the effects of leaching on changes in biomass structure.

Step 3: Testing bed agglomeration in a fluidized bed combustor; a fluidized bed combustor was used to test for defluidization in coconut husk samples that had been unwashed and then treated with water. Timing began at the start of fuel feeding and ended when the bed particles lost their fluidization state. The samples were then fed at a rate of 0.6 g/min while the combustor temperature remained constant at 800 °C.

Step 4: Analysis of agglomerated bed particles; scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) was used to determine the chemical composition of bed particles collected after the loss of fluidization conditions. Understanding the agglomeration mechanism and the main factors that drive agglomeration is made possible by the chemical composition surrounding the bed particles. FactSage (version 8.2) was used to perform a thermochemical equilibrium simulation to estimate the melting temperature of the ash [13].

3. Results and Discussion

3.1 Properties and Chemical Contents on Water Leaching Flow Rates

To determine the most appropriate conditions for removing ions from coconut husk biomass, water leaching was studied at different flow rates. Figure 3 depicts the electrical conductivity profiles over the course of the washing process and reveals that the concentration of water-soluble ions is continuously removed as time passes. The experiment was conducted 3 times for each condition, and the average values are presented to demonstrate the credibility of the data.

The electrical conductivity results during leaching varied considerably with changes in water flow rates. A significantly shorter period (672 seconds) was required to achieve the target electrical conductivity of approximately 300 μS/cm at the higher flow rate (L4, 250 ml/min)/cm compared to L2 (150 ml/min), which took 2,952 seconds. By creating more turbulence and recharging the leachate surrounding coconut husk fibers, a higher water flow rate during leaching increases mass transfer. It accelerates the dissolution of soluble ions such as potassium and chlorine. This increases the onset efficiency and rapidity of extraction. However, rapid water flow shortens the time water and biomass come into contact, which may limit the thoroughness of leaching by preventing water from fully entering the husk's porous structure. As a result, even though higher flow rates speed up ion removal, they may affect the thoroughness of leaching. To improve fuel quality, flow rate optimization is key to balancing leaching effectiveness and speed.

The uptake of water by the porous structure of coconut husk fibers is the first step in the water-leaching process. Water first enters and saturates the biomass, which makes it easier for water-soluble inorganic substances such as potassium, calcium, and chlorine to dissolve. Electrical conductivity (EC) rises during this first phase, which causes these ions to be released quickly into the leachate. As the soluble portion decreases, EC gradually declines (as seen in Figure 3). By ensuring that fresh water is continuously in contact with the biomass, the continuous-flow leaching system maintains concentration gradients that enable the mass transfer of these ions from the substance to the liquid phase. Table 1 presents the proximate analysis results for various fuel quality properties following the water leaching process.

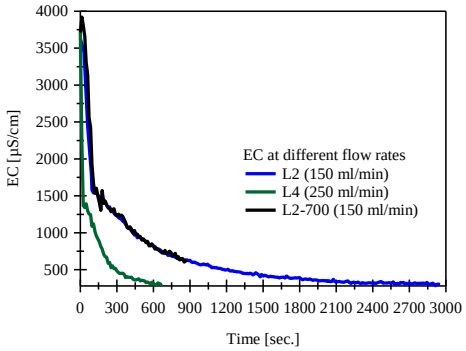


Figure 3 Electrical conductivity at different water leaching flow rates and times.

The major benefit was a reduction in ash content, from 6.70% to 2.98%–3.8% in the leached samples, a decrease of nearly 44%–56%. The benefit of reducing ash content extends equipment life, such as the heat exchanger in the boiler, due to the reduced ash amount and the high content of alkali metals and Cl in the ash.

The findings indicated insignificant changes in the higher heating value (HHV) after leaching (20.1 to 20.2-20.5 MJ/kg), but those were not found to be significant. The amount of volatile matter increased continuously across all leached samples (65.0% to 68.2%-69.9%); the increase in volatiles in leached biomass results in more complete combustion and higher combustion efficiency. Improved combustion performance means the combustion process can convert carbon monoxide (CO) more efficiently to carbon dioxide (CO_2) [12].

Table 1 The properties of coconut husk and the inorganic elements in ash at different leaching conditions.

Properties and analysis method	Raw (Non-leaching, NL)	L2 (150 ml/min)	L4 (250 ml/min)	L2-700 (150 ml/min)
Proximate analysis (wt%)				
Moisture[a], ASTM E871-80	11.1	4.9	4.9	5.3
Volatile matter[b], ASTM E872-82	65.0	69.9	69.2	68.2
Fixed carbon[c]	28.3	27.1	27.6	28.0
Ash[b], ASTM E1755-01	6.70	2.98	3.3	3.8
HHV[a] (MJ/kg,), ASTM E711-87	20.1	20.5	20.5	20.2
Oxide composition (wt% in ash), X-ray Fluorescence Spectrometry				
SiO_2	6.83	14.8	15.0	14.4
Al_2O_3	0.171	0.469	0.483	0.424
CaO	4.91	16	13.9	12.3
MgO	4.48	10.8	9.22	8.49
Na_2O	17.7	8.78	9.54	13.1
K_2O	34.2	20.4	24.2	25
Fe_2O_3	0.376	0.927	0.827	0.835
P_2O_5	3.31	3.98	3.86	3.69
SO_3	3.35	4.26	3.93	3.75
Cl	24.5	4.42	5.99	8.62
Other	0.173	15.164	13.05	9.391

[a] as received basis.
[b] as dry basis.
[c] Obtained by 100-(% volatile matter + % ash content), as dry basis.

The observed decreases in ash content and improved physical characteristics, such as increased pore volume and surface area (as shown in Table 2), are explained by mass transfer and a balanced leaching process, which depend on factors such as flow rate and leaching period.

Table 2 Surface area and total pore volume as the result of water leaching flow rates.

Sample	Leaching time (sec)	Surface area (m^2/g)	Total pore volume (cm^3/g)
Raw, NL	-	4.764	0.02032
L2 (150 ml/min)	2,952	7.228	0.02650
L4 (250 ml/min)	672	5.718	0.02465
L2-700 (150 ml/min)	876	5.554	0.02373

The raw sample had a relatively small pore volume (0.02032 cm^3/g) and surface area (4.764 m^2/g). Surface area and total pore volume were 7.228 m^2/g and 0.02650 cm^3/g at the 150 ml/min flow rate (L2), representing 52% and 30% of the values at the 10 ml/min flow rate (L1), respectively. Even with a pore volume of 0.02465 cm^3/g and a surface area of 5.718 m^2/g at 250 ml/min (L4), gains of 20% and 21%, respectively, were

observed. The observed rise in volatile matter content correlates with increased surface area and pore volume, indicating that a more open pore structure results from the removal of water-soluble alkali metals such as K and Na [17].

Concentrations of alkali metal oxides, such as Na_2O and K_2O, were significantly reduced by the leaching system. Na_2O concentration was initially 17.7%, but after leaching, the residual Na_2O was only 8.78%- 13.1%, with removal efficiencies of 26.0%–50.4%. The reduction in K_2O was from 34.2% to 20.4%- 25.0%, with removal efficiencies ranging from 26.9%- 40.4%. These removals are important because alkali metals contribute to bed agglomeration in fluidized bed combustors and promote corrosion of steel components at high temperatures. On the contrary, the relative concentrations of SiO_2 and Al_2O_3 increased from 6.83% and 0.171% to 14.4%-15.0% and 0.424%-0.483%, respectively. The higher concentrations of SiO_2 and Al_2O_3 compared to alkali metal oxides were probably due to their insolubility in water, unlike alkali metals and chlorine.

In this study, using continuous-flow water leaching on coconut husk removed potassium oxide (K_2O) by 26.9% to 40.4%, chlorine (Cl) by 64.82% to 81.96%, and reduced ash content by 43.89% to 55.92%, depending on the flow rate and leaching time. Compared with other biomass and leaching methods reported in the literature, the removal rates of K_2O, Cl, and ash differ (as shown in Table 3).

Table 3 Comparison of removal efficiencies of K_2O, Cl, and ash from different biomasses.

Feedstock	Method	Solid to liquid ratio	Time (min)	Removal efficiency, %			References
				K_2O	Cl	Ash	
Coconut husk	Continuous flow (L2, 150 ml/min)	1:73.8	49.2	40.35	81.96	55.92	This study
Coconut husk	Continuous flow (L4, 250 ml/min)	1:28.0	11.2	29.24	75.55	51.18	This study
Coconut husk	Continuous flow (L2-700, 150 ml/min)	1:21.9	14.6	26.9	64.82	43.89	This study
Corn stalk	Soaked	1:80	180	84.85	56.36	39.07	[6]
Wheat straw	Soaked	1:80	180	88.15	83.06	55.59	[6]
Wheat straw	Soaked	1:50	180	87.44	n.a.	38.2	[7]
Wheat straw	Soaked	1:10	180	87.6	n.a.	60.37	[7]
Ulva lactuca	Soaked with stirring	1:30	60	51.62	96.58	35.09	[8]
Wheat straw	Soaked with stirring	1:15	10	22.17	78.48	13.4	[9]
Empty fruit bunches	Soaked with stirring	1:15	10	23.74	90.26	37.31	[9]

For example, soaking corn stalk for 180 minutes removed 84.85% K_2O, 56.36% Cl, and 39.07% ash. Wheat straw [6, 7] soaked for 180 minutes showed K_2O removal of around 88%, Cl removal of 83%, and ash removal of 38% to 60.4%. Based on research by Singhal et al. [9], the soaked-with-stirring method was used on wheat straw and empty fruit bunches samples, with a solid-to-liquid ratio of 1:15 and a duration of 10 minutes. These conditions were compared with those in this research for L4 (250 ml/min), which used a solid-to-liquid ratio of 1:28 and a duration of 11.2 minutes. From the comparison results, the K_2O and ash removal efficiency values differed, suggesting that time and the solid-to-liquid ratio play important roles in reducing K_2O and ash.

These differences can be attributed to the operational parameters and leaching technique used. The continuous-flow system promotes sustained concentration gradients and improved mass transfer, leading to more effective extraction of soluble inorganic species such as K_2O and Cl. In contrast, simple soaking methods may suffer from slower ion diffusion and possible saturation effects, limiting removal. Moreover, the particle-size and porosity changes induced in this study (increased surface area and pore volume) likely enhance leaching efficacy by opening the biomass structure.

Decomposition and the release of volatile components occur during coconut husk burning, with temperatures ranging from 220 °C to 350 °C [18]. As a result of the relatively high potassium content in oxide form (up to 34.2%) and high chlorine content (up to 24.5%) of coconut husk, when combustion reactions take place, the compound K_2O, which has a low melting point of 740 °C [19], forms through bond breakdown. Potassium combines with chlorine to form KCl, which also has a low melting point of 771 °C [19]. This creates the potassium silicate (K_2O-SiO_2) compound when KCl reacts with SiO_2; this compound (as shown in Reaction 1) has a melting point below 800 °C [20]. Agglomeration of bed particles and defluidization in fluidized-bed combustion result from this. In addition, the boiler's heat exchange equipment is corroded due to another product, HCl. Reducing the quantities of K_2O and Cl through water washing improves biomass quality, thereby reducing corrosion and bed particle agglomeration when using biomass as fuel.

$$nSiO_2 + 2KCl + H_2O \rightarrow K_2O\ nSiO_2 + 2HCl \quad (1)$$

Where 1, 2, and 4 are equivalent to n.

In the water-leaching experiment in this research, two flow rates were tested. At the lower flow rate, the leaching time for metal alkalis (K, Na), which directly correlates with EC, was longer, with the final EC criterion set at approximately 300 μS/cm. Therefore, at the lower flow rate, a longer leaching time was required (as shown

in Figure 3), and a larger volume of water was used, indicated by the solid-to-liquid ratio, which had a positive effect on the leaching of K_2O, ash, and Cl (as shown in Table 3). Thus, the influence of leaching time is greater than that of water flow rate. Additionally, the research compared leaching at a constant flow rate of 150 ml/min across different leaching times (cases L2 and L2-700) and found that the leaching efficiencies for K_2O, Cl, and ash were higher with longer leaching times.

3.2 Characteristic of Bed Particles in Fluidized Bed Combustion

The fluidized bed combustion experiments were conducted at 800 °C with a constant fuel feed rate of 0.6 g/min to assess the ability of water leaching pretreatment to alleviate agglomeration. The defluidization times obtained under different conditions were plotted in Figure 4 to indicate the effect of bed agglomeration.

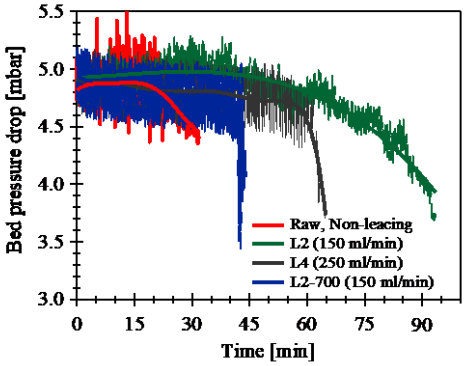


Figure 4 Bed pressure drop during combustion in a fluidized bed reactor.

The agglomeration behavior of the non-leaching sample (raw coconut husk) showed strong defluidization in only 32 minutes of operation. This rapid agglomeration of the bed is due to the high concentrations of low-melting-point alkali compounds (K_2O: 34.2%, Na_2O: 17.7%) and chlorine (24.5%) in the untreated fuel, as indicated in Table 1. These elements facilitate the formation of molten alkali silicate at very low temperatures, ultimately leading to full defluidization of the bed, as the particles would stick together.

The combustion performance under varying conditions was greatly improved during water leaching pretreatment. The L2 sample (150 ml/min, 2,952 seconds leaching time) improved the overall performance the most compared to the raw fuel, as it extended the defluidization time to 93 minutes. This high performance matches the maximum removal efficiency attained for problematic components, especially potassium oxide (40.4% removal) and chlorine (82% removal). The L4 sample (250 ml/min, 672 seconds of leaching time) had a defluidization duration of 64 minutes, which was 100% better than that of the raw fuel. The L2-700 sample had a defluidization duration of 44 minutes, which was 38% shorter than that of untreated fuel. However, the L2-700 sample also had a less favorable leaching time (876 seconds) and a higher electrical conductivity (700 µS/cm) compared to 300 µS/cm. The interrelation between the combustion capacity and the leaching capacity shows that even minimal changes in alkali content can significantly affect the time before agglomeration in the bed is established.

SEM/EDS analysis of bed material after combustion tests revealed significant compositional differences across all samples, elucidating the mechanisms leading to agglomerate formation. It also emerged during the investigation that there are layers of coating on the bed particles and sintered agglomerates, which contained elemental compositions. Relative to washed samples, the presence of Si, K, and Cl in uncooked coconut husk (NL) and the high level of ash content as indicated in Table 1, tend to produce potassium silicate compounds (K_2O-SiO_2), as shown in Reaction 1 (with a low melting point and resulting in agglomeration and rapid defluidization), according to the EDS findings of Figure 5. The X-ray fluorescence (XRF) analysis of the composition of the ash showed the same tendency as the occurrence of the elemental components surrounding the bed particles. Besides, the likelihood of bed agglomeration is directly related to the concentration of elements, particularly K and Cl, around the bed particles.

Based on experimental findings using water-finished coconut husk to test the influence on bed particle agglomeration and the defluidization period, the doubled or even tripled concentration of oxide compounds in the upgraded fuel (including SiO_2, Al_2O_3, CaO, and Fe_2O_3) compared to the concentrations present in the unleached fuel led to the large-scale chemical modification of the combustion process. According to Reactions (2) and (3), these compounds react during combustion to produce compounds called potassium aluminosilicates, including kalsilite ($KAlSiO_4$) and leucite ($KAlSi_2O_6$), with melting temperatures of over 1,500 °C and 1,600 °C, respectively [20].

$$2KCl + 2SiO_2 + Al_2O_3 + H_2O \rightarrow 2KAlSiO_4 + 2HCl \quad (2)$$

$$2KCl + 4SiO_2 + Al_2O_3 + H_2O \rightarrow 2KAl_2SiO_6 + 2HCl \quad (3)$$

The EDS compositional data (as indicated in Figure 5) from the combustion experiments served as input parameters for the simulations, which estimated the melting temperature in ash.

The K_2O-CaO-SiO_2 ternary phase diagram, which is displayed in Figure 6, was created by normalizing the primary compositions, including K_2O, CaO, and SiO_2, which were obtained from Table 1. For every EDS data set, the melting temperatures could be ordered as follows: NL (non-leaching) (600 °C-900 °C), L2-700 (900 °C–1,100 °C), L4 (1,200 °C–1,300 °C), L2 (1,300 °C–1,400 °C). The melting temperatures increased with leaching time, which reversed with water flow rates. This affected potassium removal, with a longer washing time resulting in less potassium in the fuel than in the fuel that was not washed at all. The chemical composition of solid fuel ash also consists of two classes [21]: basic oxides such as CaO, MgO, Na_2O, and K_2O with melting points of 2,927 °C, 2,832 °C, 1,132 °C, and 740 °C [19], respectively, and acidic oxides such as SiO_2 and Al_2O_3 with melting points of 1,723 °C and 2,054 °C, respectively. Some simple oxide compounds also have higher melting points, except for Na_2O and K_2O. The alkaline oxides, such as K_2O and Na_2O, are present in the sample, which also contributes to the lowering of the melting point.

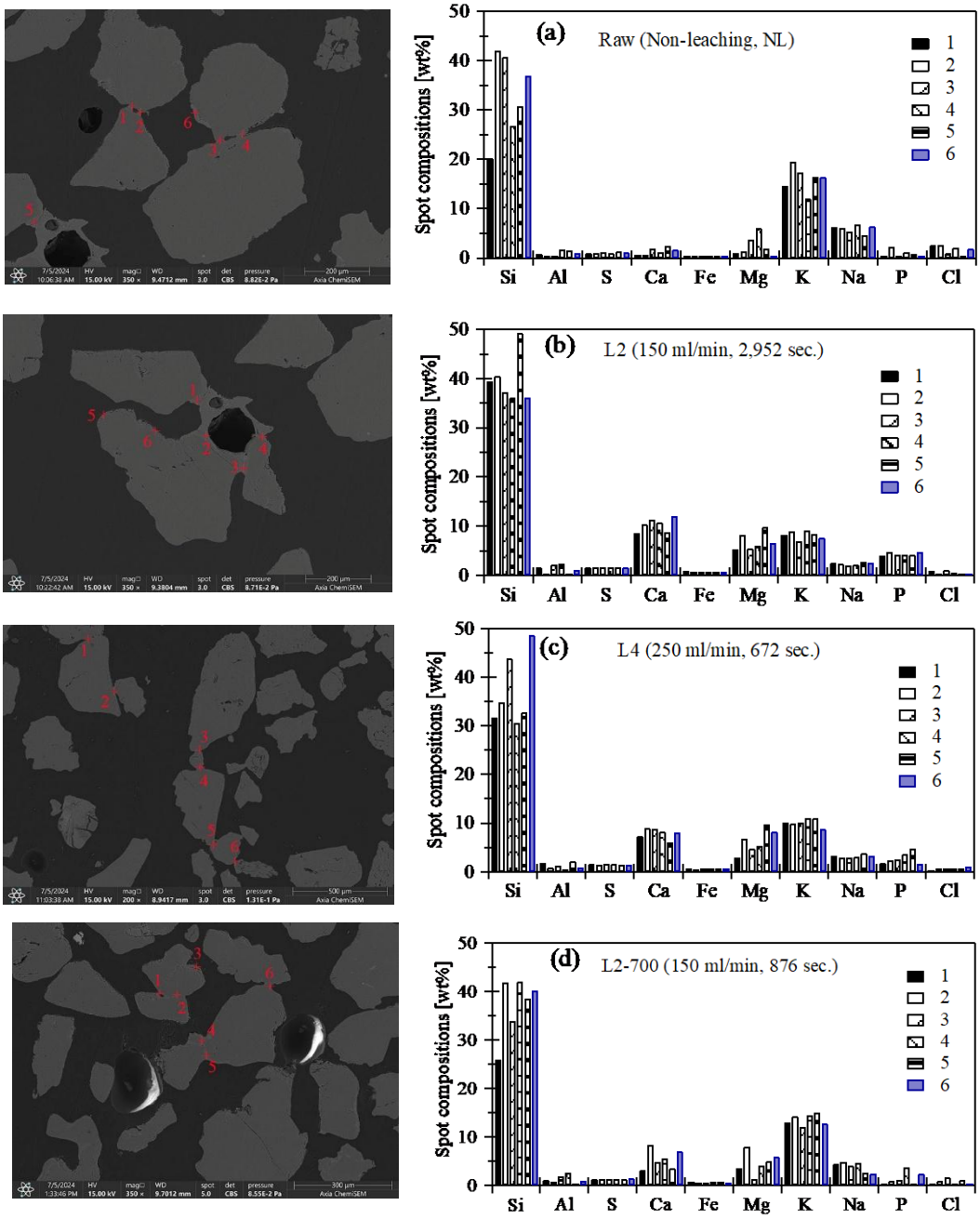


Figure 5 Analysis of bed material using SEM/EDS resulting from combustion.

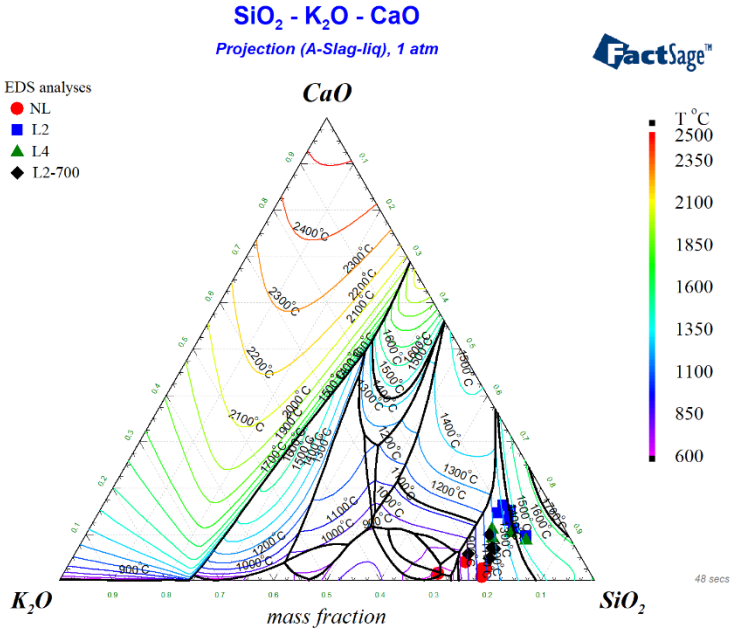


Figure 6 EDS data in the K_2O-CaO-SiO_2 ternary phase diagram.

4. Conclusions

Water leaching pretreatment effectively reduces the concentrations of soluble elements, including potassium (K), sodium (Na), and chlorine (Cl), in coconut husk biomass. This reduction improves ash melting behavior by raising the melting temperature, thereby mitigating bed agglomeration and enhancing combustion performance in fluidized-bed reactors. The water leaching method is a low-cost and cleaner technology that greatly reduced potassium oxide (26.9% to 40.4%), chlorine (64.8% to 82%), and ash (43.9% to 55.9%). The best results were obtained with a long leaching period (2,952 seconds) and a flow rate of 150 ml/min, which reduced ash to 2.98% while maintaining the heating value (approximately 20.5 MJ/kg). The pretreatment enhanced the fuel's structure by increasing the surface area by 52%, the pore volume by 30%, and the amount of volatile matter.

Water-leached samples in fluidized bed reactors were found to improve significantly during combustion. Defluidization time was also longer for the treated sample, 93 minutes, compared to the raw husk, 32 minutes. The leaching of water reduced the alkali compounds (K_2O and Na_2O) with lower melting temperatures, and the concentrations of alkali oxides with high melting points, i.e., SiO_2, Al_2O_3, CaO, and Fe_2O_3, were relatively enriched. This formed high-melting-point compounds such as kalsilite ($KAlSiO_4$), leucite ($KAlSi_2O_6$), and calcium aluminum silicates, the melting temperatures of which exceed 1,500 °C. Therefore, the ash melting temperatures increased from 600 °C-900 °C (raw husk) to 1,300 °C-1,400 °C for treated samples. The study has shown that water leaching is an effective pretreatment for coconut husk in fluidized bed combustion systems, provides viable industrial guidelines for energy and water consumption, and assesses leaching effectiveness. Future studies need to focus on scale-up and long-term operational testing.

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6. Author Contributions

Unchaisri, T.: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Supervision; Oechaiyaphum, K.: Visualization, Writing – review & editing; Chaivatamaset, P.: Methodology; Methawiriyasilp, W.: Methodology; Poosri, J.: Methodology.

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