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Prediction of Slagging and Fouling Potential of Alternative Biomass Fuel as a Bagasse Substitute in Sugar Mill Boilers

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Abstract. Boilers in sugar mills are generally designed to use bagasse as a biomass fuel. In their operations, some sugar mills are unable to provide sufficient bagasse for boiler fuel due to milling conditions that fall below their normal capacity, so they must supplement their fuel sources with biomass fuels other than bagasse, such as rice husk, wood, and sawdust. This situation can impact the performance of sugar mill boilers, which are designed specifically for use with bagasse fuel, as each biomass type has distinct characteristics. The results indicate that the use of rice husk biomass as an alternative fuel will not pose serious problems associated with slagging and fouling, as it has a low potential risk for these issues. However, the use of mahogany, acacia, or mixed wood biomass may increase the risk of slagging and fouling in boiler equipment. This is confirmed by the analysis of the ash residue contained in the boiler superheater pipe of the sugar mill taken as a research object, which shows the presence of high slagging indicators, including the parameters of base to acid ratio (B/A), iron content in ash, Fe+Ca, silica content, and silica to alumina ratio (S/A), as well as high fouling indicators in ash characterized by high total alkali parameters, fouling index, and sodium content in ash.

Keywords: Bagasse, Biomass Fuel, Boiler, Fouling, Slagging

INTRODUCTION

Biomass is living or recently dead biological material that can be used as a fuel source. The composition of biomass is predominantly attributed to various categories of materials, including but not limited to forestry products, energy sources, food crops, sugar crops, biorenewable waste, and other similar constituents (Li *et al.*, 2022). Biomass can be used directly, practically as a fuel, or indirectly by first being processed to achieve maximum results. Biomass can be utilized on both domestic and industrial scales, as well as for power generation. Biomass is widely used as a fuel for boilers in power stations because it has several advantages, including low pollution, being cheaper than fossil fuels, being safe for the environment, being easy to store and mobilize, having high combustion efficiency, being easily accessible in different places, and ensuring continuity of supply due to its renewable nature.

Sugar mill boilers are designed to utilize the primary fuel in the form of bagasse, which is generated from the cane processing waste within the mill, thereby eliminating the need

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for external fuel. This saves fuel and avoids the risks associated with using fuels other than bagasse. Several sugar mills in Indonesia are struggling to meet their processing capacity, as the availability of the main fuel for cane processing, in the form of bagasse, is diminishing due to the underutilization of the installed mill capacity. However, according to the balance sheet, the average amount of bagasse generated from the sugar cane processing process reaches approximately 30%, so the sugar mill should be able to meet its energy needs during operation and potentially have excess energy.

The boiler operating pressure in Indonesian sugar mills varies depending on the mill's design, the technology used, and the production capacity. In general, the pressure range of boilers in Indonesian sugar mills is medium to low. Several modern, large-capacity boilers utilize medium pressure, ranging from 42 to 65 bar, and steam temperatures of 450–480°C. Meanwhile, those that have not modernized their equipment typically use low-pressure boilers with a pressure range of 25–40 bar and steam temperatures between 350 and 400 °C. The furnace temperatures of both low-pressure and medium-pressure sugar mill boilers are nearly identical, ranging between 650 and 800°C.

Some sugar mills are facing a shortage of bagasse as a boiler fuel, so they usually add alternative fuels imported from outside the factory, such as husks, wood, and sawdust from various tree species, which are used simultaneously as boiler fuel, often referred to as a biomass fuel co-firing system. The use of different types of biomass in boilers can pose different risks of contamination and damage to the boiler heating equipment, such as slagging and fouling (Yunaidi *et al.*, 2020). Equipment damage, such as superheater tube rupture, has been reported in some sugar mill boilers using biomass co-fuels other than bagasse, either individually or in co-firing. On the other hand, the use of different biomass can increase the temperature of the boiler furnace, which in turn increases the potential for slagging and fouling, thereby affecting boiler performance (Harnowo & Yunaidi, 2021).

The use of biomass as a fuel can reduce over-dependence on fossil fuels and provide a source of income for its producers. On the other hand, biomass combustion has some technical limitations. The combustion temperature of some plants with short or rapid growth periods is limited to 450°C because they produce chlorine at high temperatures. Therefore, technically, biomass combustion can only be applied to small to medium-capacity power plants due to this limitation (Kong, 2010). Uncontrolled use of biomass fuel in boilers can also cause ash deposits on boiler tubes and walls, known as slagging and fouling. These ash deposits can impair the effectiveness of the heat exchanger in the boiler tubes, directly impacting the corrosion caused by high-temperature chlorine and creating a reducing atmosphere on the tube surface (Ma *et al.*, 2020). This can result in an unplanned stoppage of the production process at the plant due to mechanical failure.

Several studies have been conducted to investigate the complex phenomena of slagging and fouling (Teixeira *et al.*, 2014; Tortosa-Masiá *et al.*, 2005; Yao *et al.*, 2017). Kleinhans *et al.* (Kleinhans *et al.*, 2018) discussed in detail the physical and chemical transformations of inorganic materials during combustion, as well as the various mechanisms of ash deposition. Slagging and fouling occur when ash particles become liquid and adhere to boiler surfaces. Inorganic vapours can also condense on solid particles at lower temperatures, coating their surfaces with a thin, sticky liquid. Biomass fuels tend to have higher ash contents and lower ash sintering temperatures (Sommersacher *et al.*, 2013), while compounds such as alkali metals in ash have lower melting points and can bind to the slurry medium (Tiainen *et al.*, 2002). In a high temperature combustion environment, alkali metals and their related compounds can form deposits on the furnace walls or enter the gas phase and deposit on the surface of the final heater as vapor particles or fly ash.

Biomass also has limitations such as relatively low energy content and high investment in biomass pre-treatment equipment. The chemical composition of biomass is influenced by genetic factors and physiological characteristics of different plant species and varieties, growth phase, plant parts, fertilization and chemical protection, nutrient availability, harvesting methods, transport, storage, and other factors *(Monti et al., 2008; Vassilev et al.*, 2014). This can lead to differences in the results of studies conducted on the same plant species. Knowledge of the characteristics of plant material is crucial from an energy perspective, as each parameter affects the efficiency of biomass combustion (Loo & Koppejan, 2008; Villeneuve *et al.*, 2012). The characteristics of biomass can be determined through ultimate analysis and proximate analysis. Ultimate analysis is used to determine the content of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sometimes sulfur (S) and chloride (Cl). Meanwhile, the moisture content, volatiles, ash, and fixed carbon of the fuel are determined by proximate analysis.

Co-firing systems, which involve burning two or more different fuels in a single boiler, are widely used in sugar mills that utilize all types of existing boilers. However, some types of boilers were originally designed to burn only specific types of fuel or were not designed for co-firing. Ash deposition is a crucial parameter in biomass combustion as it is closely related to boiler operating costs. Two types of ash deposits on boiler tubes and walls are known as slagging and fouling.

Ash deposition that occurs in boiler sections with predominantly radiant heat transfer is referred to as slagging (Bilirgen, 2014). Slagging is typically caused by the formation of liquid ash particles that adhere to the surface or tube walls above the boiler furnace. The liquid form of the ash deposit resolidifies on contact with the tube wall due to the cooling effect of the tube surface, which is generally cooler than the boiler flue gas temperature. Once the initial deposit layer is formed, the surface tends to become sticky. Over time, some of the subsequent particles will be retained and adhere to the surface, causing a build-up and isolating the heat transfer process from the flue gas to the water or steam in the tube (Bilirgen, 2014).

Slagging also interferes with heat transfer and reduces local radiant heat transfer to the water tube walls of the boiler. As a result of the reduced heat transfer to the water tube walls, the flue gas temperature at the furnace outlet rises above the ash melting temperature, exacerbating the slagging problem in the inclined area of the boiler and the tubes of the convection section (Bilirgen, 2014). The presence of ash particles and other small particles will continuously increase the thickness of the deposit, so that at some point the deposit will become heavier and exceed the weight of the tube. The low melting temperature of ash facilitates slagging. As the ratio of alkaline elements (Fe_2O_3, CaO, MgO, Na_2O, K_2O) to acid elements (SiO_2, Al_2O_3, TiO_2) increases, the potential for slagging also increases. Slagging is greatly influenced by CaO, an element that readily adheres to the heat-conducting wall, and Na_2O, an element that determines the strength of the adhering ash bond. Corrosion can also occur underneath the deposits that form, significantly affecting the overall efficiency and running costs of the boiler.

Fouling refers to the accumulation of particles on the flue gas exit surfaces as they pass through the flow surfaces of the superheater, reheater, and evaporator tubes. The most influential element in this fouling is alkaline material, particularly sodium. The assessment of fouling characteristics is based on the ratio of basic to acid elements and the Na_2O content in the ash. If these values are high, the fouling tendency will generally increase. In addition, high levels of sulfur also tend to promote fouling through the formation of compounds with low melting temperatures, such as those containing bases or iron. The fouling that develops can cause problems such as a reduction in steam temperature at the superheater outlet, as well as constriction and blockage of the gas flow path. The slagging and fouling characteristics of biomass, both individually and in co-firing, can affect the heat transfer process and lead to heat losses.

Bagasse, the main fuel for sugar mill boilers, is a fibrous fuel with a moisture content ranging from 48% to 52% In contrast, sugar mill boilers are typically designed to burn bagasse with a moisture content of 42-57% and an ash content of less than 2.5%. Meanwhile, when other biomass fuels such as wood waste are added, the moisture content varies from 20% to 60%, and the ash content ranges from 1% to 15%. Consequently, the co-firing combustion system results in changes in moisture content and ash content, which in turn affect the boiler's potential performance. Variations in the moisture content and ash content of fuels, both individually and in co-firing, will result in changes in the calorific value of the combustion gas stream, which will affect the performance of the combustion chamber and superheater in the boiler (Naude, 2001).

The use of alternative biomass fuels necessitates consideration of ash content (%) and elemental composition, which includes basic elements such as Fe_2O_3, CaO, MgO, Na_2O, and K_2O, as well as acidic elements like SiO_2, Al_2O_3, and TiO_2. The characteristics of slagging and fouling in boilers are strongly influenced by the mineral composition and total sulfur in biomass fuel ash (Hare *et al.*, 2010). The acid and alkali content in the ash affects slagging in the boiler furnace and fouling of the boiler heat transfer equipment (piping, superheater, air heater). The high alkali content in biomass is the primary cause of slagging and fouling during the combustion process in boilers (Liu *et al.*, 2019; Wei *et al.*, 2017).

High ash content in bagasse fuel also reduces steam production. The higher the ash content in bagasse fuel at the same moisture content, the lower the amount of steam produced in the boiler (McIntyre, 2013).

Characteristics of biomass that differ significantly from fossil fuels in general include differences in moisture content, ash content, calorific value, and alkali metal content. Biomass ash typically has higher concentrations of alkali metals such as potassium (K), chlorine (Cl), and silicon (Si), and exhibits a wide range of moisture content and lower sulfur content. Differences in biomass fuel characteristics and ash content not only affect combustion, but also significantly alter the potential behaviour of ash to deposit at lower temperatures and melt on the boiler grate (Rein, 2016).

High concentrations of potassium and chlorine elements in biomass fuel ash, especially in the form of inorganic salt solutions such as elemental oxides, nitrates, and chlorides, can be easily volatilized during combustion, resulting in high mobility of these alkaline materials and a tendency to foul. Highly active alkali metals in the ash (e.g. K, Na, Ca, Cl) can easily form chloride phase vapor compounds that will adhere to form deposits on the boiler heat exchanger because these chloride compounds have low melting points below <800°C.

In addition, some biomass fuels contain large amounts of silica, such as straw, which contains 10% silica, and bagasse, which contains 54% silica. Silica contained in alkali metals can melt or sinter at temperatures ranging from 800 to 900°C. Alkali silica, a mixture of alkali and/or calcium chloride or sulfate, tends to deposit on boiler reactor walls and heat exchanger surfaces, causing fouling and even corrosion at relatively low melting temperatures below 700°C.

Ash with a content of 1-2% in bagasse has a relatively high silicate content (SiO_2), varying between 54% and 92.8%, and is strongly influenced by the percentage of sugar content (Brix) in the bagasse (Rein, 2016). The high silicate content in biomass increases the potential for melting ash when burned on the boiler grate (Öhman *et al.*, 2004), resulting in numerous operational problems and disrupting the sugar mill's operation.

MATERIALS AND METHODS

The research method employed to analyze biomass, from sample preparation to biomass characterization (including calorific value, proximate and ultimate tests) and ash analysis, was delineated in the research flowchart in Figure 1.

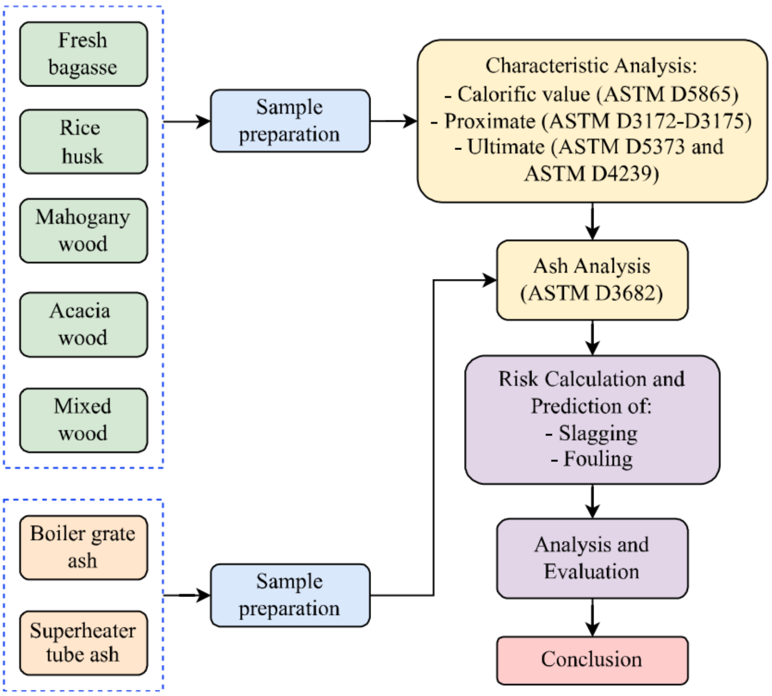

Fig. 1: Flow diagram research methods.

Materials

The materials used in the study were biomass of fresh bagasse, rice husk and mahogany wood, acacia wood and a mixture of wood, as well as 2 (two) types of combustion residue ash taken from a boiler in one of the sugar mills in Central Java Indonesia, consisting of boiler ash attached to the superheater pipe and boiler ash contained in the boiler grate or the bottom of the boiler furnace.

Characterization Analysis

Sample characteristics were obtained through various analyses, including proximate analysis, ultimate analysis, calorific value determination, and ash composition analysis. Proximate analysis was performed according to ASTM D3172-D3175, while ultimate analysis was performed according to ASTM D5373 and ASTM D4239. These standards were used to determine the content of carbon, hydrogen, nitrogen, oxygen, and sulfur using appropriate instrumentation. The calorific value was determined by analysis using a bomb calorimeter, as specified in ASTM D5865. The ash composition was analyzed using an atomic absorption spectrometer (AAS) in ASTM D3682, and the SO_3 content in the ash was determined using infrared absorption spectroscopy, as specified in ASTM D5016.

Theoretical Index to Assess Risk

The theoretical index was used to determine the tendency of slagging and fouling during biomass combustion based on the characteristics of fuel ash. Table 1 shows the range and classification of the tendency level. There were 8 (eight) slagging indicator parameters to predict slagging, including base to acid ratio (B/A), silica ratio or slag viscosity index (S_r), slagging index (R_s), iron and calcium ratio (Fe/Ca), iron content (Fe), iron and calcium content (Fe + Ca), silica content, and silica to aluminum ratio (Si/Al). Additionally, some parameters used to predict fouling tendency include the fouling index (S_f), Na content in ash, and total alkali content (Na + K).

After obtaining the value of each parameter, the risk level of each parameter was classified based on Table 1. In addition, to facilitate and simplify the evaluation of the risk level, each risk level was assigned a specific value: 0.0 for low risk, 0.5 for medium risk, and 1.0 for high risk (H. Prismantoko *et al.*, 2023; H. Putra *et al.*, 2023). Next, to predict slagging, the calculation was based on the 8 (eight) parameters in Table 1. The maximum value of slagging was 8.0. If the slagging value or score was less than 3.5, it was considered a low risk. If the slagging value was between 3.5 and 4.5, it was included in the medium-risk category, and if the slagging value was above 4.5, it was classified as high risk (as shown in Table 2).

Meanwhile, to predict fouling, the calculation is based on 3 (three) parameters, the maximum value of fouling is 3.0, if the fouling value is below 1.0 it is included in the low risk category, if the fouling value is between 1.0 - 1.5 it is included in the medium risk category, and above 1.5 it is involved in the high risk category (Kuswa *et al.*, 2023; Putra *et al.*, 2023; Suyatno *et al.*, 2023; Suyatno *et al.*, 2023).

RESULTS AND DISCUSSION

Based on the characterization results of various alternative biomasses used as boiler fuels, including calorific value analysis, proximate, and ultimate analysis, the basic properties of the research samples are quite diverse, as shown in Table 3.

Table 1. Risk classification of slagging and fouling based on ash composition.

Parameter	Formula	Values	Tendency
Slagging Indicator			
Basic to acidic ratio (Zhu *et al.*, 2019)	$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$	<0.206 0.206-0.4 >0.4	Low Medium High
Slag viscosity index (Lachman *et al.*, 2021)	$S_r = \left(\frac{SiO_2}{SiO_2 + CaO + MgO + Fe_2O_3}\right) x\ 100$	>72 65-72 <65	Low Medium High
Slagging index (Zhu *et al.*, 2019)	$R_s = (B/A) x\ S$	<0.6 0.6-2.0 >2.0	Low Medium High
Fe/Ca (Bryers, 1996; Zhu *et al.*, 2019)	$R_{Fe/Ca} = \frac{Fe_2O_3}{CaO}$	<0.3 or >3.0 0.3-3.0	Low High
Iron in ash (Suyatno *et al.*, 2023)	Fe_2O_3	<8 8-15 >15	Low Medium High
Fe+Ca (Plaza, 2013; Suyatno *et al.*, 2023)	$R_{Fe+Ca} = Fe_2O_3 + CaO$	<10 10-12 >12	Low Medium High
Silica content (Jagodzińska *et al.*, 2019; Öhman *et al.*, 2004)	SiO_2	<20 20-25 >25	Low Medium High
Silica to alumina ratio (Oladejo *et al.*, 2020; Zhu *et al.*, 2019)	$S/A = \frac{SiO_2}{Al_2O_3}$	<1.87 1.87-2.65 >2.65	Low Medium High
Fouling Indicator			
Fouling index (Garcia-Maraver *et al.*, 2017; Kitto & Stultz, 2005)	$S_f = (B/A)\ x\ (Na_2O + K_2O)$	<0.6 0.6-40 >40	Low Medium High
Na in ash, if $Fe_2O_3 + CaO + MgO < 20$ $Fe_2O_3 + CaO + MgO > 20$ (Putra *et al.*, 2023; Zhu *et al.*, 2019)	Na_2O	<1.2 >1.2 <0.3 >3.0	Low High Low High
Total alkali (Jeong *et al.*, 2019)	$Na_2O + K_2O$	<2 2-3 >3	Low Medium High

Table 2. Score or value of slagging and fouling.

Risk Level	Low	Medium	High
Slagging	<3.5	3.5 – 4.5	>4.5
Fouling	<1	1 – 1.5	>1.5

The initial analysis for biomass fuel characterization is crucial for energy calculations and the early prediction of potential issues in power plants (Kozlov *et al.*, 2015). All results of the proximate and ultimate analyses are on a dry basis, except for moisture content and calorific value, which are on an as-received basis.

The results showed that the lowest calorific value is attributed to fresh bagasse, which amounts to 2073 kcal/kg, while the highest calorific value is owned by mixed wood, reaching 4538 kcal/kg. The wood mixture has a high calorific value because it is generally composed of wood waste originating from sugar mills. Examples of such waste include sawn teak wood and sengon wood, which possess a high calorific value. The high calorific value of the wood mixture can also be attributed to its low moisture content. The calorific value of wood (mahogany, acacia, and a mixture of various types of wood) is much higher than the calorific value of bagasse as the main fuel for boilers in sugar mills. The moisture content of fresh bagasse is significantly higher than that of rice husk and wood. This is because bagasse obtained directly from the sugar mill's juice extraction process is generally used as boiler fuel without drying. The variation in calorific value and moisture content of various alternative biomass fuels compared to the main fuel (bagasse) in boilers, whether used individually or together (co-firing) can result in changes in the calorific value of the combustion gas flow which affects the performance of the furnace and superheater in the boiler (Naude, 2001; Panchal *et al.*, 2016), so that operational adjustments are needed on the boiler when used. The presence of high moisture content and large biomass particles in the boiler furnace may result in delayed combustion and lower peak flame temperatures (Heinzel *et al.*, 1998).

Table 3. Biomass sample characteristics of fresh bagasse, rice husk, mahogany, acacia, and mixed woods.

Content	Symbol & Unit	Fresh bagasse	Rice husk	Mahogany wood	Acacia wood	Mixed wood
Calorific value	kcal/kg	2073	3248	4278	3831	4538
Proximate:						
Moisture	% adb	49.50	7.85	8.01	8.21	7.75
Ash	% adb	1.55	20.67	7.85	15.97	3.54
Volatile	% adb	41.95	57.96	67.35	60.92	71.25
Fixed carbon	% adb	7.00	13.52	16.79	14.90	17.46
Ultimate:						
Carbon	C	45.21	42.03	42.83	38.78	45.26
Hydrogen	H	5.57	5.91	4.85	4.70	5.27
Oxygen	O	41.43	39.14	36.12	31.33	38.86
Nitrogen	N	0.35	0.52	0.21	0.32	0.43
Sulphur	S	0.03	0.05	0.01	0.03	0.07

The ash content of rice husk is the highest, at 20.67%, significantly higher than that of bagasse, which has a content of 1.55%. Meanwhile, the ash content of the wood varied between 3.54% and 15.97%, with the highest ash content found in acacia wood. When compared to other solid fuels such as coal, biomass tends to have a higher ash content. The ash content of biomass ranges from 0.5% to 20% (Llorente & García, 2005). The high ash content of biomass is likely due to the large quantities of silicon (Si) and iron (Fe) involved in ash deposition. A high silicon (Si) composition in biomass tends to result in greater ash deposition (Garcia-Maraver *et al.*, 2017). The presence of high levels of alkali (Na and K) in mahogany wood has been shown to result in the formation of low eutectic alkali-aluminosilicates (Ghazidin *et al.*, 2023). Furthermore, the presence of a high Fe content in mahogany and acacia wood can accelerate the development of ash deposits, due to its low melting point (Rushdi *et al.*, 2004).

High ash content can also accelerate the filling of ash in the boiler combustion chamber and reduce the amount of steam produced in the boiler [20]. An increased ash content in fuel can reduce combustion efficiency and increase the oxygen content in flue gases (Ninduangdee & Kuprianov, 2018). The volatility value of bagasse is relatively lower than that of rice husk and wood, which is due to its relatively high-water content. The higher volatility value of biomass has a positive effect on the ease of ignition of fuel, a faster combustion process, and an increase in boiler efficiency.

The sulphur content in bagasse and all biomass test samples commonly used as alternative boiler fuels in sugar mills showed relatively small values, ranging from 0.01% to 0.07%. This is an advantage because, when used as boiler fuel, this alternative fuel does not produce adverse environmental effects and does not contribute to the formation of NO_x and SO_x gas emissions (Baxter, 2005; Wang *et al.*, 2021).

The results of the ash analysis of the biomass composition of bagasse, rice husk, three types of wood, and two types of combustion residue ash found in the boiler at the sugar mill, namely boiler ash attached to the superheater pipe and boiler ash found in the boiler grate, can be seen in Table 4.

Table 4. Ash analysis of biomass samples and ash residue from combustion in sugar mill boilers.

Ash analysis	Symbol	Fresh bagasse	Rice husk	Mahogany wood	Acacia wood	Mixed wood	Boiler grate ash	Superheater tube ash
Silica	SiO_2	74.99	95.52	37.94	45.74	15.26	85.46	51.20
Aluminium	Al_2O_3	5.46	0.33	21.65	21.01	6.97	1.52	1.09
Iron	Fe_2O_3	3.73	0.13	11.82	13.58	5.95	0.64	19.54
Calcium	CaO	4.50	0.85	21.88	13.89	53.56	2.07	2.75
Magnesium	MgO	1.62	0.32	0.16	0.63	3.95	1.42	0.74
Titanium	TiO_2	0.093	0.001	0.99	1.03	0.08	0.05	0.10
Natrium	Na_2O	0.78	0.15	1.67	1.42	2.24	0.26	1.65
Kalium	K_2O	5.43	1.73	1.58	1.13	1.52	2.84	8.92
Phosphor	P_2O_5	1.27	0.46	1.42	1.10	6.39	2.39	3.08
Sulphur	SO_3	0.59	0.43	0.72	0.39	3.37	3.30	10.64

Silica has a beneficial effect because its high melting point increases the ash fusion temperature (Hariana *et al.*, 2023; Niu *et al.*, 2016). Conversely, the strong interaction between silicon (Si) and potassium (K) in biomass, particularly agricultural biomass, can lead to severe ash-related issues during combustion due to the low melting point of K-silicate. These compounds stick to other particles to form slag in the boiler (Zevenhoven *et al.*, 2012).

The highest Al_2O_3 content was found in mahogany and acacia wood, while the lowest content was found in rice husk and bagasse. When biomass contains impurities, aluminum can form aluminosilicate. An elevated level of aluminosilicates in biomass has been demonstrated to increase the ash fusion temperature, thereby enabling the capture of alkaline vapor during combustion (Niu *et al.*, 2016). Acacia wood has the highest Fe_2O_3 content, followed by mahogany wood, bagasse, and finally rice husk. Mahogany wood has the highest CaO content, followed by acacia wood, with bagasse and rice husk having the lowest. The presence of high levels of iron and calcium in biomass can have a detrimental impact on the boiler's performance. This is because the low melting point of biomass allows it to form slag when exposed to excessively high temperatures (Y. Wang *et al.*, 2016; Wei *et al.*, 2022).

Fresh bagasse and acacia wood have the highest MgO content. MgO can improve combustion characteristics and reduce slagging and fouling in boilers (Akiyama *et al.*, 2011). The ash analysis revealed that bagasse exhibited the highest potassium (K_2O) content, followed by rice husk and mahogany wood. The presence of potassium in biomass has been demonstrated to decrease the ash fusion temperature (Yao *et al.*, 2020; Zhang *et al.*, 2021). This phenomenon has been shown to induce a series of ash-related complications during the combustion process (Li *et al.*, 2019; Pérez-Jeldres *et al.*, 2018), including slagging, fouling, sintering, agglomeration, and corrosion (Iáñez-Rodríguez *et al.*, 2020).

From the ash analysis, a theoretical index was calculated to predict the risk of slagging and fouling based on several parameters, as shown in Tables 1 and 2. The results of the slagging and fouling prediction calculation of several biomass and ash samples in the sugar mill boiler are shown in Table 5.

Based on the calculation of the theoretical index to predict the risk of slagging and fouling as shown in Table 5, the biomass of bagasse and rice husk has a low slagging potential with a risk value below 3.5 on a scale of 8. The biomass of mixed wood has a moderate level of slagging risk. Mahogany wood and acacia wood biomass have a high risk of slagging in the boiler. Bagasse and rice husk biomass have a low slagging potential in terms of B/A ratio, silica ratio (slag viscosity index), and Fe+Ca, whereas all wood biomass exhibits the opposite condition. A high B/A ratio above 0.4 in wood biomass can increase the tendency for deposits to occur (Garcia-Maraver *et al.*, 2017). The high content of CaO and Fe_2O_3 in wood biomass is also a contributing factor to increased slagging intensity in boilers (Pintana *et al.*, 2014).

The higher silica (SiO_2) content in bagasse and rice husk compared to woody biomass may also increase the potential for serious slagging (Wahab *et al.*, 2020). In general, silica is the dominant element in biomass fuels that can form silicate sticky liquids that play a role in slagging formation (Gilbe *et al.*, 2008; Öhman *et al.*, 2004). This is also evidenced by the relationship between silica content in biomass fuel ash and the fraction of fuel ash that forms slag (Öhman *et al.*, 2004); hence,

Table 5. Calculation and prediction of slagging and fouling of biomass samples and ash of combustion residue from sugar mill boilers.

Parameter	Symbol	Biomass					Boiler ash	
		Fresh bagasse	Rice husk	Mahogany wood	Acacia wood	Mixed wood	Boiler grate ash	Superheater tube ash
Slagging Indicator								
Basic to acidic ratio	B/A	0.20	0.03	0.61	0.45	3.01	0.08	0.64
Slag viscosity index	S_r	88.39	98.66	52.84	61.94	19.39	95.39	68.97
Slagging index	R_s	0.01	0.01	0.01	0.01	0.21	-	-
Fe/Ca	$R_{Fe/Ca}$	0.83	0.15	0.54	0.98	0.11	0.31	7.11
Iron in ash	Fe	3.73	0.13	11.82	13.58	5.95	0.64	19.54
Fe+Ca	R_{Fe+Ca}	8.23	0.98	33.70	27.47	59.51	2.71	22.29
Silica content	Si	74.99	95.52	37.94	45.74	15.26	85.46	51.20
Silica to alumina	S/A	13.73	289.45	1.75	2.18	2.19	56.22	46.97
Slagging risk value		**3(8)**	**2(8)**	**5.5(8)**	**6(8)**	**3.5(8)**	**3(8)**	**5.5(8)**
Fouling Indicator								
Fouling index	R_f	1.24	0.06	1.99	1.15	11.33	0.26	6.78
Na in ash	Na	0.78	0.15	1.67	1.42	2.24	0.26	1.65
Total alkali	Alk	6.21	1.88	3.25	2.55	3.76	3.10	10.57
Fouling risk value		**1.5(3)**	**0(3)**	**2(3)**	**1.5(3)**	**2(3)**	**1(3)**	**2(3)**

*Color description:
- low
- medium
- high

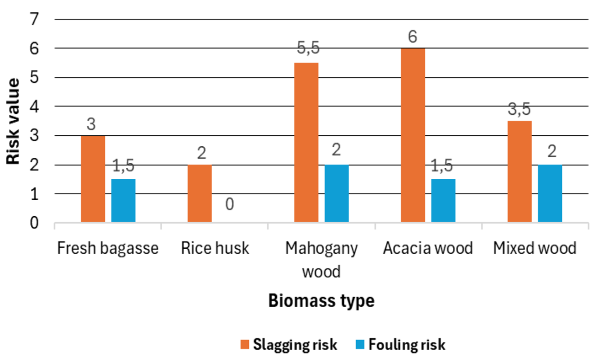

Fig. 2: Comparison results of slagging and fouling risk values of different types of biomasses

silica content can be used as an indicator of slag formation. Meanwhile, the high Al_2O_3 content in woody biomass can reduce the silica-to-alumina (S/A) ratio, which can lower the risk of slagging. Alumina in biomass acts as an additive to reduce the potential for slagging in woody biomass (H. Prismantoko *et al.*, 2023). Based on Table 5 above, the overall slagging risk value indicates that acacia wood biomass poses the highest risk, with five parameters exhibiting a high risk and two parameters a medium risk. The lowest slagging risk value is found in rice husk biomass, which has only two high-risk parameters and six low-risk parameters. In contrast, bagasse has three high-risk parameters and five low-risk parameters, as shown in Figure 2.

Based on the analysis of combustion residue ash in sugar mill boilers, it is also evident that the composition of ash samples taken from the bottom of the furnace or boiler grate differs from that of ash attached to the superheater pipe. Table 5 shows that the indication of slagging in the superheater pipe has a high risk value of 5.5 on a scale of 8, while the boiler grate has a low risk value. The composition of ash attached to the superheater pipe shows that the content of iron, calcium, sodium, potassium, and sulfur is higher when compared to the ash found in the grate boiler. The silica content in the boiler grate is greater than in the superheater pipe. The higher iron or Fe_2O_3 content in the superheater pipe ash indicates the presence of corrosion in the pipe, which occurs due to ash scaling on the pipe's surface. If left unchecked, this can cause leaks during operation.

The lowest fouling risk value characteristic of rice husk biomass is 0 (zero) on a scale of 3, followed by bagasse biomass with a medium risk value of 1.5 on the same scale. This is due to the low Na_2O content in the ash. The Na_2O content in the ash is used in all fouling indicator calculations and is a crucial factor determining the indicator measurement (Hare *et al.*, 2010). While the fouling risk value for woody biomass tends to be medium to high (1.5-2.0), this is directly proportional to its high Na_2O content compared to bagasse and rice husk. The K_2O content in ash is also an important factor, as it has a low melting point of 700 ^oC (Vassilev, Baxter, & Vassileva, 2013). Bagasse and rice husk have a relatively higher K_2O content than woody biomass, although the difference is not very significant. The fouling risk characteristics of boiler ash also show that the highest risk occurs in the superheater tube. The high Na_2O and K_2O content in the ash deposited on the superheater tube indicates that the total alkali content in the ash is very high, resulting in fouling. Based on the data presented in Tables 4 and 5, the use of rice husk biomass fuel as an alternative fuel or co-firing will not cause serious slagging and fouling potential in the boiler. In contrast, the use of wood biomass fuel as an alternative fuel for boilers in sugar mills may increase the potential for slagging and fouling in the superheater tubes and other boiler components.

Currently, the vast majority of boilers in sugar mills continue to rely on bagasse as a primary fuel source for their operations. This is because bagasse is produced as a byproduct of the sugarcane-to-sugar conversion process. Consequently, the utilization of bagasse contributes to a reduction in the operational costs of the factories. In the event of a shortage of bagasse, alternative fuel sources must be developed to ensure a stable energy supply. In the context of utilizing bagasse or other solid biomass as a boiler fuel, effective management of the temperature and distribution of combustion air supply within the boiler or furnace is paramount to avert the occurrence of slagging and fouling. The majority of sugar mills in Indonesia operate their boilers at temperatures ranging from 650°C to 800°C. The use of wood biomass fuel as a co-firing agent with bagasse tends to increase the temperature of the boiler's combustion chamber (Harnowo & Yunaidi, 2021).

Inadequate air supply can lead to two primary issues: slagging due to high temperatures and fouling resulting from incomplete combustion of ash. An excess of air supply has been demonstrated to reduce furnace temperature, thereby diminishing the likelihood of slagging. However, this increase in air supply can also result in the transportation of greater quantities of light ash into the superheater and economizer, thereby augmenting the probability of fouling in these components. Conversely, insufficient air supply to the furnace can result in localized combustion reaching extreme temperatures, which can exceed the ash melting point. This, in turn, can increase the potential for slagging. Incomplete combustion results in the production of unburned carbon, which, in turn, leads to an exacerbation of slag accumulation within the furnace. Furthermore, the presence of elevated carbon residue levels in the ash has been shown to enhance the adhesive properties of the fouling layer, thereby complicating its removal (Basu, 2013; Saidur *et al.*, 2011; Vassilev *et al.*, 2013; Werther *et al.*, 2000). Uneven air distribution has been shown to induce local hot spots, resulting in a significant escalation of slagging in specific areas. Additionally, the flue gas flow becomes inconsistent, potentially causing fouling in only a portion of the convection pipes, making it difficult to predict and address the issue.

CONCLUSIONS

A study was conducted to assess the slagging and fouling potential of alternative biomass types for use as fuel in sugar mill boilers. The results showed that the highest slagging potential occurs with the use of acacia wood, with a risk value of 6 on a scale of 8, followed by mahogany wood with a risk value of 5.5 and mixed wood with a risk value of 3.8. On the other hand, the highest risk of boiler fouling occurs when mahogany or mixed wood is used as fuel, with a risk value of 2 on a scale of 3. The use of rice husk as a boiler fuel has the lowest potential for slagging and fouling compared to wood biomass, even lower than bagasse, which is the main fuel for sugar mill boilers. Analysis of the sugar mill boiler ash also shows that ash attached to the superheater tube has a higher indication of slagging and fouling than ash contained in the boiler grate. Since the moisture content of fresh bagasse is still quite high, the calorific value of all alternative biomasses used as fuel is higher than that of fresh bagasse biomass. Nevertheless, fresh bagasse remains the predominant choice as boiler fuel for sugar mills, primarily due to its relatively low risk of potential slagging and fouling, as well as its optimal economic efficiency. The ash content of rice husk is significantly higher than that of bagasse or woody biomass, which can accelerate the accumulation of ash in the boiler furnace, thereby reducing combustion efficiency. The volatility of all alternative biomass types tested is also higher than that of bagasse, which facilitates combustion and increases boiler efficiency.

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