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Research Article

A techno-economic and environmental analysis of co-firing implementation using coal and wood bark blend at circulating fluidized bed boiler

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Abstract. The study aimed to explore the effects of biomass co-firing of coal using acacia wood bark at circulating fluidized bed (CFB) boiler coal-fired power plant with 110 MWe capacity. The analysis focused on main equipment parameters, including the potential for slagging, fouling, corrosion, agglomeration, fuel cost, and specific environmental factors. Initially, coal and acacia wood bark fuel were blended at a 3% mass ratio, with calorific values of 8.59 MJ/kg and 16.59 MJ/kg, respectively. The corrosion due to chlorine and slagging potential when using wood bark was grouped into the minor and medium categories. The results showed that co-firing at approximately 3% mass ratio contributed to changes in the upper furnace temperature due to the variation in heating value, high total humidity, and a less homogeneous particle size distribution. Significant differences were also observed in the temperature of the lower furnace area, showing the presence of a foreign object covering the nozzle, which disturbed the ignition process. A comparison of the seal pot temperature showed imbalances as observed from the temperature indicators installed on both sides of boiler, with specific fuel consumption (SFC) increasing by approximately 0.17%. During the performance test, the price of acacia wood bark was 0.034 USD/kg, resulting in fuel cost of 0.023355 USD/kWh, adding 0.061 cent/kWh to coal firing cost. Despite co-firing, the byproducts of the combustion process, such as SO2 and NOx, still met environmental quality standards in accordance with government regulations. However, a comprehensive medium- and long-term impact evaluation study should be carried out to implement co-firing operations using acacia wood bark at coal-fired power plant. Based on the characteristics, such as low calorific value, with high ash, total moisture, and alkali, acacia wood bark showed an increased potential to cause slagging and fouling.

Keywords: co-firing, biomass, wood bark, circulating fluidized bed boiler, corrosion, slagging, fouling, emission, fuel cost

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1. Introduction

The total share of global renewable energy consumption is projected to increase from 18% in 2020 to 82% by 2050. During the transition phase, modern biomass and hydrogen are expected to play more significant roles, contributing 16% and 14% of energy mix by 2050, respectively (World-Energy-Transitions-Outlook-2023, n.d.). Biomass co-firing program has also been effective in reducing greenhouse gas emission, serving as cost-effective strategy for developing biomass supply infrastructures. For example, 1 TWh of electricity from biomass co-firing substitutes 0.9 MT of fossil CO_2 emission in Europe (Cutz *et al.,* 2019). Indonesia has also observed a significant advancement in renewable energy generation, experiencing a 0.99% increase in energy usage, which is equivalent to approximately 939.1 million barrels of oil in 2021. This growth is distributed across various sources including biogas, oil, electric power, natural gas, coal, liquefied petroleum gas, biodiesel, and biomass. Additionally, the country possesses considerable untapped potential for renewable energy generation, estimated at 419 GWe. This includes diverse sources such as 75 GWe, 23.7 GWe, 32.6, 207.8, 60.6 GWe, and 19.3 GWe from hydropower, geothermal energy, bioenergy, solar power, wind, and small-scale hydropower (Pambudi *et al.*, 2023). The strategic expansion of renewable energy is essential for the substantial reduction of greenhouse gas emission, thereby mitigating the impacts of extreme meteorological phenomena. It also ensures the provision of reliable, timely, and economically viable energy.

The transition program from fossil to renewable energy aims to reach 23% by 2025 (Triani *et al.,* 2022). An electric company in Indonesia, namely PT PLN (Persero), has implemented biomass co-firing program at 52 power plants with a total generation capacity of 19 GWe ("Kaleidoskop 2022, Implementasi Co-Firing di PLN Hasilkan 575,4 GWh Listrik Bersih," 2023). By 2025, the Indonesian government aims to initiate co-firing practices in coal-fired power plants (CFPP), facilitated by the state-owned enterprise PLN, with a combined capacity of approximately 18,000 MWe. The anticipated

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average co-firing ratio is projected to be 10%, corresponding to an annual biomass use of 9 million tons (Arifin *et al*., 2023).

Biomass has been studied for fuel co-firing on CFPP, considering the particle size, energy value, density, and ash content characteristics (Cahyo, Hapsari *et al.,* 2022). Experiments have also been conducted using sawdust in an approximately 5% blend-in boiler with a 330 MWe capacity (Tanbar et al., 2023). In Circulating Fluidized Bed Boiler, trials including palm kernel shell co-firing in proportions ranging from 5% to 10% were conducted to assess operational performance, fuel cost-effectiveness, and emission characteristics (Cahyo, Alif, Hapsari *et al.,* 2021; Cahyo, Hariyostanto, *et al.,* 2022). Additionally, Pulverized Coal Boiler with tangential firing systems and a 315 MWe capacity were tested for co-firing with wood pellets to observe the impact on boiler efficiency, emission, and operational parameters. (Cahyo, Alif, Aditya, *et al.*, 2021; Cahyo *et al*., 2020a). Further studies have investigated co-firing capabilities of other biomass resources such as corn cobs (Daba & Hailegiorgis, 2023), rice husks (Prasara-A & Gheewala, 2017), solid recovered fuel (Tanbar *et al.,* 2023), recovered derivative fuel (Soleh *et al.,* 2019), waste wood (Putra *et al.,* 2024), coconut shells (Inayat *et al.,* 2018), and oil palm empty fruit bunches. By the end of 2023, studies on new types of biomass as alternative co-firing fuel were conducted on a laboratory-scale. This includes characterization of palm frond and stem biomass (Sadig *et al.,* 2017; Umar *et al.,* 2020) and co-firing wet hog-sludge fuel with coal in combustion tests, which contribute to higher sulfur dioxide emission (Laursen & Grace, 2002) or direct co-firing testing at CFPP.

Previous studies have shown that the main factors affecting co-firing potential are the price of biomass and carbon, including the alkali index (Cutz et al., 2019). Therefore, there is a need to evaluate the impact of biomass co-firing on power generation on laboratory-scale and full-scale experimental tests in boiler CFPP. The laboratory-scale studies focused on discussing the characteristics of biomass as fuel by comparing their properties in power plants, including parameters from proximate and ultimate analyses, ash composition, ash fusibility temperature, chlorine content, etc. Meanwhile, full-scale experiments investigated the effects of co-firing on changes in performance, the emission produced, and the potential for slagging, fouling, and corrosion. A numerical simulation study of co-firing has been carried out in an octagonal tangentially fired boiler. The result showed that by increasing biomass blend ratio from 0 to 20%, the mean temperature of the primary combustion zone decreased from 1,327.35 ^{0}C to 1,298.05 ^{0}C (Du et al., 2024).

Co-firing with palm kernel shells has shown the potential to reduce furnace exit gas temperature (FEGT), bed temperature, SO_2, and NO_x emission and increase fuel consumption (Cahyo, Alif, Hapsari, *et al.,* 2021). Furthermore, it saves fuel cost by ranging from 0.23 cents/kWh to 0.31 cents/kWh compared to coal firing condition, assuming 1 USD = 16,250 IDR). Other studies reported that co-firing with a 5% and 10% ratio using palm kernel shell contributed to an increase in the seal pot temperature, bed, and air chamber pressure. Moreover, the specific fuel consumption (SFC) during co-firing has decreased with range from 1.51% to 1.90% (Cahyo, Hariyostanto, *et al.*, 2022).

A performance assessment using sawdust biomass was carried out on 21 CFPP across the Java-Bali grid, including Sumatra and Kalimantan networks (Cahyo, Hapsari *et al.,* 2022). The results showed that furnace exit gas temperature typically decreased during co-firing process. The substantial volatile matter content in the sawdust biomass significantly facilitated the combustion process within the furnace due to higher flammability. The influence of co-firing on the mill outlet temperature was marginal, as the tempering air input was adjusted to stabilize the outlet temperature. However, the load on the mill increased after the introduction of biomass fuel, which possessed a lower Hardgrove Grindability Index (HGI) compared to coal. Concerning emission, co-firing tests have shown a propensity to diminish levels of SO_2, as presented in Table 1.

The increase in the proportion of wood pellets to 5% in co-firing has been found to reduce furnace exit gas temperature and slightly raise the SFC, along with a decrease in emission of CO, NO_x, and SO_2 (Cahyo *et al.,* 2020). According to a previous,

Table 1
Biomass Co-firing Performance and Emission Effect on Boiler CFPP

Biomass	Co-firing Ratio (% of biomass)	Boiler Type	Impact	Reference
palm kernel shell	5; 10	CFB	$T_{upper\ furnace}$ ↗ T_{bed} ↗ $T_{sealpot}$ ↗ Fuel cost ↘ SFC ↘ SO_2 ↗ NO_x ↗ CO ↗ *Minor Corrosion*	(Cahyo, Hariyostanto, *et al.*, 2022)
sawdust	5	PC	FEGT ↘ SFC ↘ SO_2 ↘ NO_x ↘ Minor Corrosion	(Cahyo, Hapsari, *et al.*, 2022; Tanbar *et al.*, 2021)
wood pellet	1; 3; 5	PC	FEGT ↘ SFC ↘ SO_2 ↗ NO_x ↘ SFC ↗	(Cahyo, Alif, Aditya, *et al.*, 2021; Cahyo *et al.*, 2020a)
corncob	0.2; 0.25; 0.3; 0.4; 0.45 g/g	furnace lab scale	Combustion efficiency ↗	(Daba & Hailegiorgis, 2023)

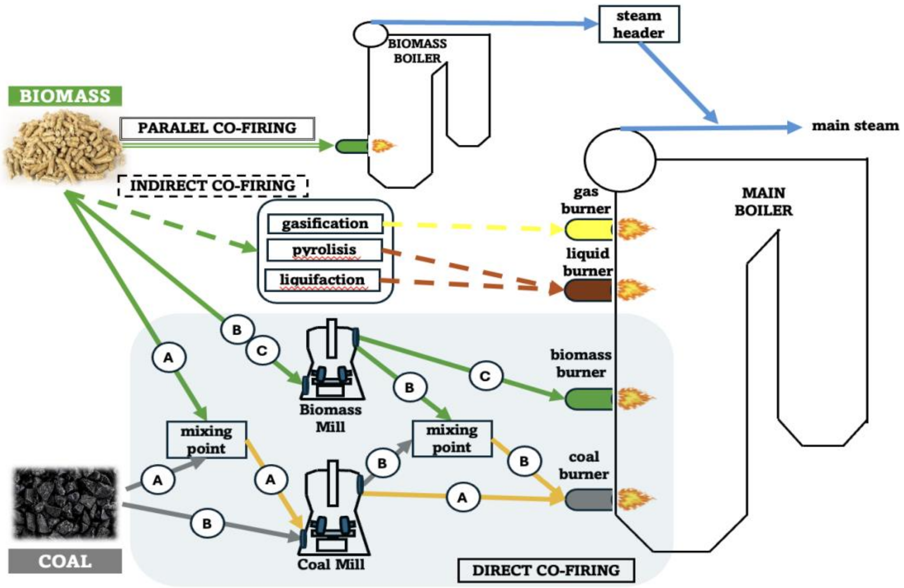

Fig 1. Biomass co-firing technology

a 5% wood pellet co-firing regime reduced FEGT by approximately 15°C, which is 1.27% below the baseline scenario. SO_x emission ranged from 8.22% to 20.51%, while the NO_x levels in the flue gas experienced a 3.62% increase, with a 4.40% rise in SFC (Cahyo, Alif, Aditya, *et al.,* 2021).

Despite the numerous benefits, biomass also creates particular challenges, including the agglomeration of bed solids, corrosion, and degradation of superheater tubes downstream. In ash content, these challenges are often attributed to chlorine and unwanted elements such as potassium. An effective solution to mitigate agglomeration is by maintaining the combustion in the lower part of the furnace under 700^{0}C. This phenomenon decreases the potential formation of a molten eutectic mixture with silica sand. Additionally, introducing more air into the more diluted upper zone of the furnace can increase temperatures to facilitate the burning of gaseous compounds (Basu, 2015).

1.1. Co-firing Technology

As shown in Figure 1, the three main co-firing technologies that have been developed include direct, indirect, and parallel (Arifin *et al.,* 2023; Aviso *et al.*, 2020; Basu, 2018; Dam-Johansen *et al.*, 2012; Milićević *et al.*, 2021; Roni *et al.*, 2017; Xu *et al.,* 2020). Direct co-firing is conducted with biomass and coal burned together in the same boiler. This process includes several methods to mix fuel materials, as shown in Figure 1.

Method A in Figure 1 illustrate the mixing of biomass and coal is conducted before the pulverizer, such as at the stockpile (Cahyo, Hariyostanto, *et al.*, 2022; Dian *et al.,* 2021) or on the conveyor line (Cahyo *et al.,* 2020b). Coal and biomass are mixed, forming fuel mixture, followed by storing in fuel tank (bunker). Subsequently, the mixture is supplied to the mill and passes through a coarse powder separator, with the coarse particles being recycled back into the ball mill (Wang *et al.,* 2021).

The handling and feeding system for biomass fuel is implemented separately from coal fuel system. After passing through each pulverizer, biomass, and coal are burned in the same burner, as shown in Figure 1 method B. This method is implemented at a mid-level co-firing ratio with modifications to fuel handling system and auxiliary equipment. Direct co-firing is a separate system from the handling process to the entry into boiler, where biomass is directly co-fired with coal-fired boiler. Biomass and coal are handled and pulverized separately as shown in Figure 1 method C. Subsequently, biomass fuel burns with coal through dedicated burners in the lower furnace (Mo *et al.*, 2023). This method is carried out with a high co-firing ratio and modifications to boiler system and auxiliary equipment.

Indirect co-firing entails converting biomass into syngas through gasification (Basu, 2018; Inayat, Sulaiman, Hung, *et al.,* 2018) and transforming to gaseous or liquid fuel by pyrolysis and liquefaction processes. This is followed by the combustion of fuel directly in boiler, with additional apparatus such as a gasifier. Initially, biomass is transformed into syngas with the aid of a gasification unit before placing in the combustion chamber of coal-fired boiler (Xu *et al.*, 2020). Meanwhile, in parallel co-firing, biomass combustion occurs in a distinct boiler. The resultant steam is channeled into the system of the existing coal-fired boiler.

Among these technologies, direct co-firing is widely recognized as the most cost-effective, eliminating the need for substantial alterations to the existing power infrastructure, and avoiding major additional capital expenditures (Basu, 2018; Mo *et al.,* 2023). For example, in the United States, North America, and Canada, direct co-firing is the norm in biomass CFPP, with approximately half of the mill using wood-based feedstocks such as pellets, chips, waste, agricultural by-products, forest

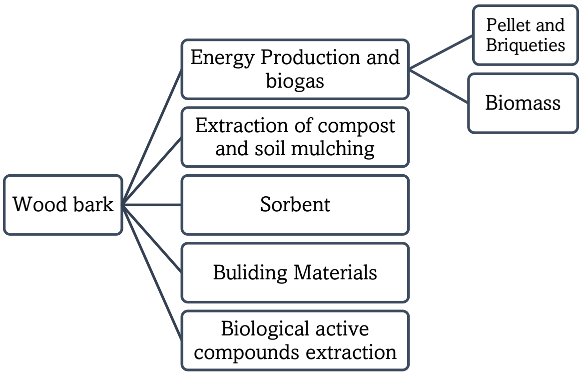

Fig. 2. Opportunity uses of wood bark (Jansone *et al.,* 2017)

Table 2
Wood bark Proximate and Ultimate Analysis (Park et al., 2021; Parmar, 2017)

Parameters	Unit	WB1	WB2
Proximate Analysis			
Moisture	% wt	6.6	
Volatile Matter	% wt	67.3	
Fixed Carbon	% wt	24.8	
Ash	% wt	1.3	1.5
Ultimate Analysis			
Carbon	% wt	51.1	47.8
Hydrogen	% wt	5.8	5.9
Oxygen	% wt	42.9	45.4
Nitrogen	% wt	0.2	0.4
Sulfur	% wt	-	0.1
Gross Calorific Value	MJ/kg	22.7	19

Table 3
Fuel Composition

Parameters	Unit	SNI*	Coal	Wood Bark	Mix Fuel
Proximate Analysis					
Moisture	% wt	< 35	35.59	48.15	34.77
Volatile Matter	% wt	-	32.14	35.79	33.60
Fixed Carbon	% wt	< 12	26.45	7.71	25.70
Ash	% wt	< 4.5	5.82	8.36	5.92
Ultimate Analysis					
Carbon	% wt	-	40.83	22.88	40.81
Hydrogen	% wt	-	3.04	2.51	3.16
Oxygen	% wt	-	13.48	17.74	14.38
Nitrogen	% wt	-	0.64	0.24	0.58
Sulfur	% wt	< 0.5	0.59	0.13	0.37
Gross Calorific Value	MJ/kg	>12.56	16.59	8.59	16.66
Lower Calorific Value	MJ/kg	-	16.54	8.54	16.61
Chlorine	% wt	< 0.04	na	na	0.04
Hargrove Grindability Index		-	48.09	na	47.75
Initial Deformation Temperature	°C	<1,150	na	1,060	1,115
Ash Analysis					
SiO_2	% wt	-	na	62.90	38.50
Al_2O_3	% wt	-	na	12.24	14.01
Fe_2O_3	% wt	-	na	8.43	14.12
CaO	% wt	-	na	3.10	24.82
MgO	% wt	-	na	1.14	3.47
Na_2O	% wt	< 5	na	0.35	0.21
K_2O	% wt	< 15	na	1.13	0.95
TiO_2	% wt	-	na	na	0.59
P_2O_5	% wt	-	na	na	0.09
Mn_3O_4	% wt	-	na	na	0.47
SO_3	% wt	-	na	na	6.55

Source: *Indonesian National Standard (SNI) No 9032 (2021)

debris, domestic and urban waste, for co-firing with coal (Agbor *et al.*, 2014; Yacob *et al.,* 2021).

1.2. *Wood bark Characteristic*

Bark is the layer located outside the cambium, comprising both conductive and non-conductive phloem and the rhytidome (Wenig *et al.*, 2021). Due to its unique chemical composition, bark biomass serves as an excellent raw material for technological processes and a staple in biorefining. Furthermore, it offers versatility in producing various bio-based products, including biomass, pellets, and briquettes for fuel, as shown in Figure 2.

Compared to wood, bark contains a significantly higher concentration of lignin, ranging from 25% to 45%, and relatively lower levels of polysaccharides. Regarding inorganic elements and ash content, bark has phosphorus and sodium concentrations of approximately 1.9 and 13.5 times higher than wood, respectively. The ash content of stem bark varies from 4.8% to 6.0% by mass, compared to 0.52% to 0.89% found in wood (Chahal & Ciolkosz, 2019). Previous studies show that wood bark, lignocellulosic biomass from a furniture factory (WB1), has high volatile matter with low ash and sulfur content (Park *et al.*, 2021). The ash content for wood bark (WB2), ranges from 1.3 to 1.5% (Parmar, 2017), as shown in Table 2. Generally, the majority of biomass fuel is often characterized by low nitrogen and sulfur levels, which defer significantly ash content.

Previous investigations have shown that wood bark has the potential to be used as fuel due to its energy content. However, there is a need to consider specific parameters, such as ash content, alkalis, and chlorine, which are capable of causing slagging, fouling, and corrosion. After examining fuel characteristics presented in Table 3, performance testing experiments were conducted at CFPP. In full-scale experimental studies, co-firing trials using wood bark were conducted for the first time in Indonesia, which is the novelty of this study. Direct co-firing tests with wood bark and coal in 100 MWe circulating fluidized bed boiler coal-fired power plants were also carried out without any modifications due to the cost-effectiveness and applicability of the experiments.

Based on the background above, this study aimed to describe the effect of co-firing on the changes in the main parameters, the economic cost of fuel, environmental emissions, slagging, fouling, and agglomeration. The results provide a valuable improvement on previous co-firing studies that address related topics. This includes slagging and fouling (Ghazidin *et al.,* 2023a; Hafizh *et al.,* 2023; Hariana, Prabowo, *et al.*, 2023; Hariana, Prismantoko, *et al.*, 2023; Novendianto *et al.*, 2024; Putra et al., 2024; Putra, Kuswa, Ghazidin*, et al.,* 2023; Suyatno *et al.,* 2023a), economic and environmental effect (Mo *et al.,* 2023), carbon emission reduction and management (Aviso *et al.,* 2020; Sun *et al.,* 2021; Xie *et al.,* 2023), flame characteristic and stability (Lu *et al.,* 2008), and change in energy (Mehmood *et al.,* 2012).

2. Methodology

2.1. Experimental Method

The experiment was carried out using direct co-firing method without any modifications at the circulating fluidized bed boiler Unit 2, with a capacity of 100 MWe, located in Balikpapan, Kalimantan, Indonesia, as shown in Figure 4. This test method was conducted in previous studies using another biomass (Cahyo, Alif, Hapsari, *et al.,* 2021; Cahyo, Hariyostanto, *et al.,* 2022). For the 3% ratio of co-firing test, with a duration of 4 hours, 8.4 tons. Of wood and bark were unloaded at coal yard. Biomass handling process uses existing heavy equipment to arrange wood bark in coal yard, as shown in Figure 3. Subsequently, the mixing process with coal was carried out using heavy excavator equipment. Fuel-feeding process of wood bark-coal mixture was transferred to coal bunker through an emergency hopper.

The operating parameters were observed in the baseline and co-firing conditions. First, the baseline condition, where the test was carried out when the unit was operating with 100% coal. Second, the operating parameters were observed in co-firing conditions. Data were collected when the load setting reached 100 MWe gross for consecutive four hours. The main critical parameters observed included coal flow, total airflow, outlet gas temperature, bed temperature, air chamber pressure, main steam temperature, and main steam pressure. Operational parameter data were collected within this duration at intervals of 30 minutes and started after the stabilization period.

Fig. 3 Wood bark feedstock

2.2. Evaluation method

The direct method used to determine SFC was described by (Cahyo, Alif, Hapsari, *et al.,* 2021) and gross electrical energy production (in kWh) was recorded using a kWh meter. Meanwhile, the consumption of fuel (in kg) was picked from coal feeders recording data. Fuel cost was calculated using SFC performance data added to coal and wood bark fuel prices. The equation for calculating SFC is expressed as follows (Wang *et al.*, 2023) :

$$SFC = \frac{Fuel\ consumption}{Power\ Generation} \qquad (1)$$

where: SFC is specific fuel consumption, Fuel consumption is the total fuel consumed during the test, and power generation is the total power generated during the test.

The ash settling potential can be evaluated by using the ratio of base-to-acid (B/A) on a molar basis. The B/A ratio is a value used to estimate the fusion characteristic, the potential slagging, and the ash content of metals that are mixed during firing process to form salt with a low melting point. The B/A ratio is calculated by the following equation (Cahyo *et al.,* 2023; Ghazidin *et al.,* 2023b; Putra *et al.,* 2024) :

$$\frac{B}{A} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} \qquad (2)$$

where: B/A is base-to-acid ratio, Fe_2O_3, CaO, MgO, Na_2O, and K_2O are the values of oxides in ash as bases properties, SiO_2, Al_2O_3, and TiO_2 are the values of oxides in ash as acid properties.

Slagging is formed when the sticky ash particles melt or soften, sticking to the heat transfer surface. The tendency of slagging formation is measured using slagging index of solid fuel. Moreover, fouling is a dry settlement from the ash particles or condensation at the organic component that vaporizes easily on the surface of heat transfer. The tendency for the formation of fouling is measured using fouling index of solid fuel. In this study, the slagging and fouling index was calculated by the following equation (Cahyo *et al.*, 2023):

$$R_s = \frac{B}{A}\ x\ Fe_2O_3 \qquad (3)$$

$$R_f = \frac{B}{A}\ x\ (Na_2O + K_2O) \qquad (4)$$

where: Rs is slagging index, Rf is fouling index, B/A is base-to-acid ratio, Fe_2O_3, Na_2O, and K_2O are the values of oxides in ash as base properties.

The sulfation potential of chlorides was calculated and evaluated on a molar basis using 2S/Cl (Cahyo, Hapsari, et al., 2022), where a value > 8 shows a minor risk category of Cl-induced active oxidation. Furthermore, the 2S/Cl ratio value < 4 denotes a major risk category of Cl-induced active oxidation.

The agglomeration was evaluated based on the characteristics of solid fuel. In agglomeration tendency evaluation, the total values < 1.0 were considered low, while 1.0–1.5 and 1.5 were medium and high, respectively. The agglomeration index was calculated by the following equation (Ghazidin *et al.,* 2023b; Putra *et al.*, 2024; Suyatno *et al.*, 2023b):

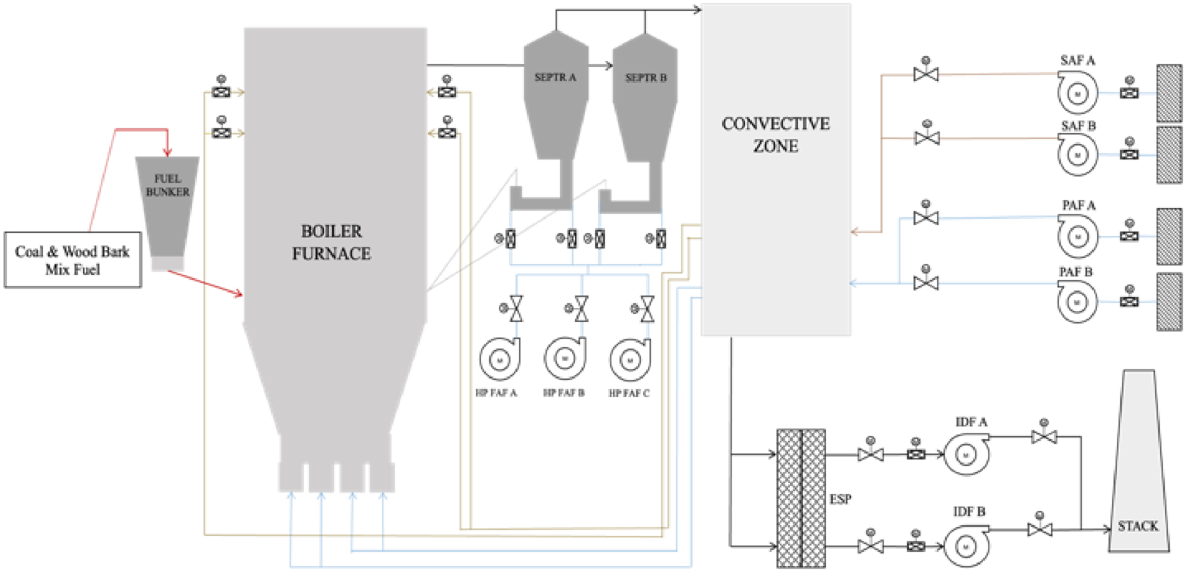

Fig. 4 Co-firing Testing Schema

$$AgI = \frac{Na_2O + K_2O}{2S + Cl} \quad (5)$$

where: AgI is the agglomeration index, Na_2O and K_2O are the value of oxides in ash as base properties, S is sulfur content in fuel, and Cl is chlorine content in fuel.

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3. Result and Discussion

3.1. Fuel Characteristic

The characteristics of coal and acacia wood bark were observed by comparing the results of ultimate and proximate analyses obtained from suppliers between low-rank coal used in power plants and wood bark. According to the laboratory results presented in Table 3, the total moisture content of acacia wood bark was very high due to the alkali content such as silica (SiO_2). Biomass fuel usually contains more moisture and chlorine than coal. Moreover, the ash content of wood bark is also more significant than coal's (Bhuiyan *et al.,* 2018). Based on the results, calorific values of acacia wood bark and coal were found at 8.59 MJ/kg and 16.59 MJ/kg, respectively. This was in line with previous studies, where biomass calorific value tended to be lower than coal or fossil fuel (Lalak *et al.*, 2016; Luo & Zhou, 2017; Ohm *et al.*, 2015; Özyuğuran & Yaman, 2017).

When compared with the Indonesian National Standard (SNI) 9032-2021, this acacia wood bark biomass showed ash and moisture content exceeding the maximum permitted limits. Additionally, the carbon content, gross calorific value, and initial deformation temperature (IDT) of ash in a reduced atmosphere are below the minimum allowable limit.

3.2. Bed Temperature and Furnace Exit Gas Temperature

Figure 5 shows that when coal-firing bed temperature tends to be more stable than in co-firing conditions. The average bed temperature during the 3% wood bark co-firing test decreased by 0.32%, which was still within the limit range for normal operating conditions of approximately <950 °C.

Bed temperature distribution in coal cut-off region was closely related to the mixing and diffusion characteristics of coal particles in the dense phase zone. Moreover, different feeding rates and operational adjustments could cause variations in the distribution and temperature, impacting boiler's overall thermal behavior (Dong *et al.,* 2024). To maintain bed temperature, the operator could adjust fuel feed, air supply (primary and secondary), and ash removal rates (Arjunwadkar *et al.,* 2016).

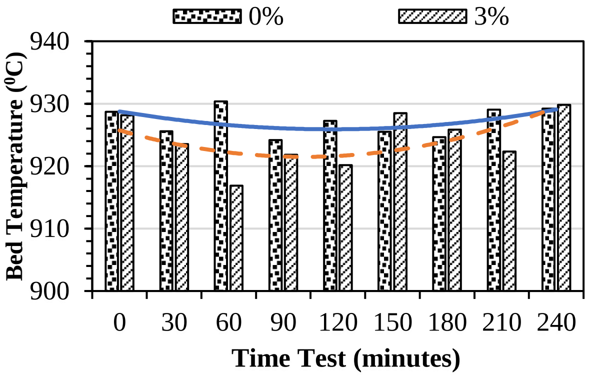

Fig. 5 Comparison of bed temperature on co-firing and coal firing condition

The furnace exit gas temperature during co-firing showed a gradual increase over time, as presented in Figure 6. This proves the analysis of the ignition delay, showing that a longer increase in FEGT can cause a higher total humidity, a less homogeneous particle size distribution, and elevated heat difference. Biomass fuel particle shape variation has a significant effect on combustion efficiency. Generally, incomplete combustion tends to increase when biomass particle size is large (Bhuiyan *et al.*, 2017) . Table 4 shows that the grain or particle size passing through the crusher outlet for the ideal size for circulating fluidized bed boiler of 4-6 mm, is still below 70%. This supports previous estimates that the particle size distribution has not been mixed homogeneously or evenly between coal and acacia wood bark. The size of biomass feed must be balanced, avoiding excessively large to hinder fluidization and not small to bypass the cyclone. In systems where bed materials are predominantly derived from feed ash, the particle size distribution directly influences the furnace's hydrodynamics. Therefore, a higher proportion of fine particles in solid fuel can lead to an increased combustion rate within the furnace's upper, and less dense area, with some particles

Table 4
Particle Size Distribution of Mix Fuel Before and After Crusher

Fuel Size Distribution (mm)	Unit	Inlet Crusher	Outlet Crusher
>50	%	5.88	1.08
>22.4	%	29.41	11.84
>16	%	11.55	7.81
>11.2	%	11.33	9.83
>4.75	%	16.78	21.80
<4.75	%	25.05	47.64

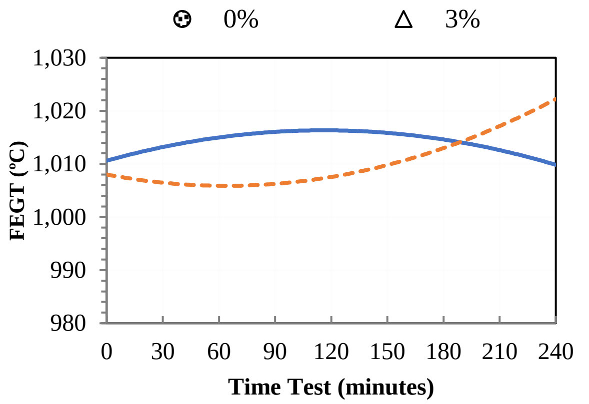

Fig. 6 Comparison of flue gas exit gas temperature (FEGT) on co-firing and coal firing condition

combusting in the cyclone or exiting without being burned. (Basu, 2015).

3.3. Seal pot Temperature

Seal pot is the area between the outlet cyclone and the return line to boiler. The temperature of this area must be maintained below the limit as the abnormal condition can give a unit trip signal. The average seal pot temperature during co-firing tends to be lower than coal firing, as shown in Figure 7. Meanwhile, there is a temperature imbalance in the seal pot between boiler sides A and B during coal firing and co-firing. When the temperature on side B is very different from the average value, there is a tendency for agglomeration, which is capable of affecting the sand bedding. Furthermore, agglomeration can occur within the seal pot/loop seal and external heat exchanger because the fluidization velocity is lower than in the combustor (Arjunwadkar *et al.*, 2016).

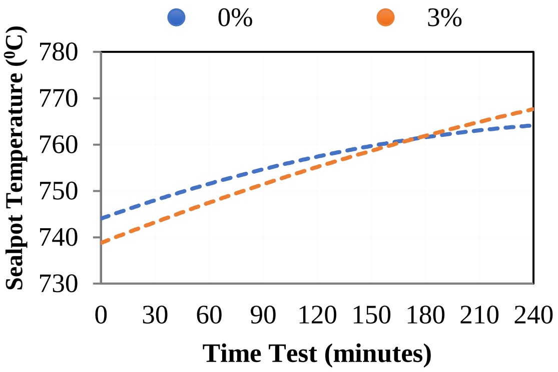

Fig. 7 Comparison of seal pot temperature on co-firing and coal firing conditions

3.4. Smoke and Carry Over

Biomass characteristics are similar to bituminous coal, which possesses, high density, hardness, volatility, and is more environmentally friendly with low sulfur content. When the combustion composition of biomass is proper, there is a tendency for significant reduction or absence of black smoke. However, side effects of black smoke can be experienced in the stack when fuel in boiler burns at high temperatures, reaching from 800°C to 1000°C or higher, and there are components in biomass fuel that do not burn entirely, or poor combustion control (Streets, 2006). In this study, there was no visible black smoke on the stack observed during the 3% wood bark co-firing test, showing the absence of carryover in the exhaust gas.

3.5. SFC

Co-firing 3% wood bark at a load of 100 MWe gross showed an increase in SFC of 0.17% from 0.7059 kg/kWh to 0.7071 kg/kWh. The results of coal firing and co-firing tests using wood bark showed that the resulting power load had not changed significantly. With a 3% wood bark ratio, the ability of coal feeder was still effective normally according to individual capacity.

3.6. Economic Fuel Cost

Economically, considering the actual price of biomass wood bark during co-firing test, (1 USD = 16,250 IDR) which is 0.034 USD/kg, co-firing 3% wood bark increases fuel cost by 0.26% compared to coal-firing, as shown in Table 5. The increase in fuel cost is influenced by the higher cost of biomass than coal. Furthermore, the lower energy content of biomass wood bark leads to higher fuel consumption.

3.7. Emission Product Characteristic

The average NO_x emission shows an upward trend from 285 mg/Nm^3 to 307 mg/Nm^3. Compared with the previous month's data report, the SO_2 emission value during coal-firing was 523 mg/Nm^3. Based on fuel analysis, the comparison between sulfur content of coal and biomass is 0.59% and 0.13%, respectively. This shows that wood bark co-firing has the potential to produce lower SO_2 emission. According to government rules, the gas emission from the 3% wood bark co-firing test, including SO_2 and NO_x, are still below the maximum levels of 550 mg/Nm^3. The NO_x emission produced depends on biomass nitrogen content and the oxygen supplied during the burning process. Moreover, the use of biomass contributes to increasing delicate particulate matter and the concentration of CO_2 emission (Triani *et al.*, 2022).

3.8. Slagging, Fouling, Corrosion and Agglomeration

Ash derived from several types of biomass is highly concentrated with reactive chemical substances, including sodium, potassium, sulfur, phosphorus, and chlorine, potentially resulting in increased corrosion (Basu, 2015). Based on the

Table 5
The Comparison of Fuel Cost

Parameter	Unit	Coal-Firing	Co-Firing
SFC	kg/kWh	0.7059	0.7071
Coal Price	USD/kg	0.033	0.033
Wood bark Price	USD/kg	-	0.034
Mixing Fuel Price	USD/kg	0.033	0.033
Fuel Cost	USD/kWh	0.023295	0.023355

Table 6
Slagging, Fouling, Corrosion, and Agglomeration

Parameter	Unit	Value	
Ash Fusion Temperature		Reducing	Oxidizing
IDT	^{0}C	1,115	1,170
ST	^{0}C	1,150	1,180
HT	^{0}C	1,150	1,200
FT	^{0}C	1,160	1,220
2S/Cl Ratio		27.27	Minor
Base to Acid Ratio (B/A)		0.82	Medium
Ash Fusion		High or Severe	
Slagging Index (Rs)		1,122	High
Fouling Index (Rf)		0.95	High
Agglomeration Index (AgI)		0.09	Low

calculations presented in Table 5, fuel mix consisting of 97% coal and 3% wood bark acacia biomass shows a minor corrosion category, while the ash deposition is in the medium category. Moreover, the slagging and fouling potentials are significantly high. Another study shows that the addition of certain biomass waste tends to increase slagging fouling compared to coal combustion (Hariana *et al.,* 2022; Putra *et al.,* 2024; Suyatno *et al.*, 2023a). This shows the need to consider the increased risk of slagging and fouling under conditions of a higher co-firing ratio.

Agglomeration refers to the process where small particles amalgamate into larger clusters. This process occurs in fluidized bed when the temperature surpasses the ash fusion temperature (AFT), as determined by ASTM standard tests. The ash fusion temperatures are recorded at several key points, including initial deformation temperature (IDT) when the ash begins to deform, and softening temperature (ST) where a spherical mass is observed. Other essential points as shown in Table 6 include hemispherical temperature (HT) during the formation of hemispherical shape, and flow temperature (FT) when the tash completely melts to a flowing liquid.

In circulating fluidized bed boiler, agglomeration issue is often associated with fuel containing high alkali metals. When combined with elements such as sulfur, chlorine, silica, and phosphorus, these metals create low-melting-point compounds known as eutectics (Arjunwadkar *et al.*, 2016). To overcome these challenges, mitigation strategies that have been proven effective include controlling biomass content according to boiler's design. The operating temperatures of both the loop seal and the external fluidized bed heat exchanger below fuel's ash fusion point should be maintained. Additionally, bed additives can be used, including iron oxide (Fe_2O_3), kaolin, and other clays.

Alternative bed materials such as limestone, mullite, magnesite, calcite, clay, and bone ash have been suggested as viable options (Arjunwadkar *et al.,* 2016). Previous studies have shown that incorporating up to 50% by weight of biomass into fuel mix did not substantially increase agglomeration risk (Putra, Kuswa, Prabowo, *et al.,* 2023). Based on the calculations presented in Table 6, fuel mix consisting of 97% coal and 3% wood bark acacia biomass showed a low category of agglomeration.

4. Conclusion

In conclusion, this study showed that acacia wood bark possessed calorific value of 8.59 MJ/kg, significantly lower than the Indonesian national standard minimum permitted limit of 12.59 MJ/kg. Although the content of ash, water, and fixed carbon exceeded the limits permitted by SNI, the silica oxide content (SiO_2) value was relatively high. Wood bark as fuel showed minor potential for corrosion, and medium ash deposition, while slagging and fouling were in the high category. A comparison of lower and upper furnace temperature parameters showed a reasonably high margin. Furthermore, there was fuel quality factor from wood bark with very high moisture, which showed the potential for clumping, causing agglomeration and poor fluidization. A comparison of the temperature seal pot parameters showed an imbalance condition as observed from the temperature indicators installed on sides A and B. This was due to poor combustion quality and monitoring of fuel and bed material quality. The increase in SFC from coal firing to co-firing was insignificant, showing an approximate value of 0.17%. Regarding the actual price of biomass during co-firing test at 0.034 USD/kg, fuel cost was 0.023355 USD/kWh, resulting in PLN incurring an additional fuel cost of 0.061 cent/kWh compared to coal-firing. Emission products, SO_2 and NO_x, in the 3% wood bark co-firing test still complied with the Environmental Quality Standards by the Minister of the Government Regulation.

This study showed the outcome of assessing the short-term effects of co-firing mode boiler operation, the medium- and long-term effects were not examined. Therefore, a comprehensive medium- and long-term impact evaluation study should be carried out to implement co-firing operations using acacia wood bark at the power plant. Emphasis should focus on the characteristics of the acacia wood bark sample, particularly the low calorific value content, as well as high ash content, and total moisture alkali content, with the potential to cause slagging and fouling. The particle size distribution required monitoring to maintain boiler's combustion quality. Further analysis should evaluate the particle size of coal, and bed material entering boiler must comply with standards. Additionally, the continuity of the supply of wood bark biomass required further investigation.

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