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UTILIZATION OF COCOPEAT, EMPTY FRUIT BUNCH, AND PALM KERNEL SHELL AS RENEWABLE ENERGY FEEDSTOCK IN BOILER

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ABSTRACT
The increasing generation of biomass waste from coconut and palm oil industries presents both environmental challenges and opportunities for renewable energy utilization. This study evaluates the potential of cocopeat, empty fruit bunch (EFB), and palm kernel shell (PKS) as alternative fuels in boiler applications through fuel characterization, blending analysis, and thermochemical performance modeling. This research aims and objective to characterize the three wastes, determine the best composition mixture as boiler fuel, and estimate the potential exhaust gas emissions. This research uses laboratory testing methods, calculation of calorific value, and estimation of exhaust gas emissions (CO_2, SO_2, NO_2) using stoichiometric calculations and steam production modeling based on energy balance principles. The test was carried out by comparing cocopeat pellets (PECO); a mixture of 50% cocopeat and 50% EFB (BCO); PKS; and EFB. The results showed that 10% PECO, 30% EFB, 60% PKS has a high calorific value of 17.05 MJ/kg. Furthermore, NO_2 emissions and steam production rate are decreased to 3.42% and 7.93% than 20% PECO, 40% EFB, 40% PKS. This is due to the high value of the coconut shell fraction (PKS), which produces a high calorific value. Furthermore, the cocopeat mixture, consisting of 10%BCO, 30%EFB, and 60%PKS, has low NO_2 emissions and can produce high steam in boilers. This indicates that cocopeat can be used as a new fuel when mixed with EFB, thereby maximizing the utilization of coconut waste and reducing environmental impact.

Keywords: *Cocopeat, Empty Fruit Bunch, Palm Kernel Shell, Boiler, Emissions.*

1. Introduction

Indonesia is one of the largest palm oil producers globally, generating substantial quantities of solid biomass residues annually. Palm oil can be used as alternative fuel with blending with diesel fuel (Bhikuning et al., 2020; Bhikuning et al., 2023; Aldebaran et al., 2024; Bhikuning et al 2018). In addition, the remaining palm oil producers can be used as an alternative biomass fuel such as Empty fruit bunch, palm kernel shell and cocopeat. Empty fruit bunches (EFB) account for approximately 20–23% of fresh fruit bunch (FFB) weight, while palm kernel shells (PKS) contribute around 5–7% (Ahmad et al., 2016; Windiastuti et al., 2022). Considering Indonesia’s crude palm oil production reaches tens of millions of tons per year, the corresponding generation of EFB and PKS is estimated at tens of millions of tons annually. In addition, coconut processing industries produce large volumes of by-products such as cocopeat and coconut husk, which remain underutilized despite their lignocellulosic richness (Abdul Rahim et al., 2020; Vieira et al., 2024).

Improper waste management practices, including open dumping and uncontrolled burning, pose significant environmental risks. Open burning of biomass residues contributes to greenhouse gas emissions, particulate matter formation, and local air pollution (Harahap et al., 2023; Setiawan et al., 2025). High moisture content in EFB and cocopeat also leads to methane formation during anaerobic decomposition, further increasing environmental burdens. Although PKS is widely utilized as boiler fuel and export biomass commodity (Handaya et al., 2022; Pawlak et al., 2020; Yek et al., 2021), EFB and cocopeat are still partially underutilized due to technical challenges such as high ash content, high moisture levels, and inconsistent combustion properties. Previous studies have investigated individual biomass types for thermochemical conversion. EFB has been studied for combustion, gasification, and co-firing applications (Chiew et al., 2013; Booneimsri et al., 2018; Ismail et al., 2017; Setiawan et al., 2024), while PKS has demonstrated favorable calorific value (18–21 MJ/kg) and low ash characteristics suitable for boiler applications (Junga et al., 2020; Sulaiman & Abdullah, 2011). Cocopeat has been improved through torrefaction and pelletization processes to increase its calorific value and combustion stability (Alamsyah et al., 2016; Borel et al., 2021). Co-firing strategies combining palm biomass residues have also been explored to reduce greenhouse gas emissions and improve energy efficiency (Harahap et al., 2023; Hariana et al.,2023).

However, most prior studies focus on single biomass utilization or binary blending systems, with limited comparative analysis of ternary mixtures involving cocopeat, EFB, and PKS specifically for industrial boiler performance. Existing research on emission optimization generally evaluates palm oil residues such as EFB, mesocarp fiber, and PKS (Setiawan et al., 2025; Harahap et al., 2023; Lin et al., 2021), but does not incorporate cocopeat as a significant blending component. Moreover, there is insufficient integration between: 1) Comparative calorific performance of multiple blending ratios, 2) Element-based emission estimation (CO_2, SO_2, NO_2) for boiler-scale application, and 3) Quantitative steam production modeling under realistic boiler efficiency conditions. Thus, the scientific gap lies in the limited systematic evaluation of optimized cocopeat–EFB–PKS ternary mixtures for maximizing boiler energy output while minimizing gaseous emissions.

The specific technical problem addressed in this study is: how to determine an optimal ternary blending ratio of cocopeat, EFB, and PKS that simultaneously enhances calorific value, maintains combustion stability, reduces nitrogen oxide formation, and ensures feasible steam generation in biomass boilers. Without proper optimization, excessive EFB may increase ash-related fouling, while high nitrogen content may elevate NO_2 emissions (Vega et al., 2019), potentially reducing boiler efficiency and environmental compliance.

This study offers clear novelty and scientific contributions by providing a comprehensive proximate, ultimate, and calorific characterization of cocopeat–EFB–PKS ternary mixtures as a theoretical foundation for multi-biomass fuel evaluation. From a technical perspective, the research identifies an optimized blending formulation that enhances calorific value while controlling key emission precursors, particularly nitrogen and sulfur compounds. Practically, the study quantitatively estimates steam production capacity under defined boiler efficiency assumptions to assess the feasibility of industrial-scale application. Environmentally, it evaluates potential CO_2, SO_2, and NO_2 emissions derived from elemental composition analysis, thereby determining blending scenarios that are energetically efficient and environmentally preferable for biomass boiler systems.

By integrating biomass characterization, blending optimization, emission estimation, and steam production modeling, this research strengthens the scientific positioning of multi-biomass utilization strategies and contributes to the development of sustainable boiler fuel alternatives in Indonesia’s biomass energy sector.

2. Literature Review

2.1 Cocopeat

Cocopeat, also called coir pith, is a fibrous byproduct from processing coconut husks. It mainly contains lignocellulosic materials, which include cellulose (25.8%), hemicellulose (20-25%), and lignin (28.5%). These components play a key role in thermal processes like combustion, gasification, and pyrolysis (Krishnapillai et al., 2020; Alamsyah et al., 2016). Because of this composition, cocopeat has good potential as a renewable solid fuel. When dried and pelletized, cocopeat has a heating value between 15 and 18 MJ/kg, which can differ based on its moisture content and density (Borel et al., 2021). This energy value is similar to that of other common biomass fuels, making cocopeat suitable for industrial boilers, biomass stoves, and co-firing in thermal power plants. Additionally, cocopeat’s high volatile matter content and low ash residue improve combustion efficiency. However, its high initial moisture content, often over 70% in its raw state, requires pre-drying or torrefaction to improve its fuel quality and energy density (Alamsyah et al., 2016). Besides direct combustion, pyrolysis of cocopeat can produce biochar, syngas, and bio-oil, which contribute to different renewable energy options. Combining cocopeat with other biomass residues, like EFB or PKS, in co-firing schemes also enhances fuel blending characteristics and reduces emissions.

2.2 Empty Fruit Bunch

Empty Fruit Bunch (EFB) is one of the main solid residues produced during palm oil milling, making up about 20 to 23% of the total fresh fruit bunch (FFB) weight. It mainly consists of lignocellulosic biomass, which contains hemicellulose (around 25 to 35%), cellulose (around 35 to 45%), and lignin (around 20 to 30%). This composition makes EFB a good candidate for thermochemical conversion into bioenergy (Ahmad et al., 2016; Windiastuti et al., 2022; Yulistiani et al., 2026; Mohd Fuad et al., 2024).

The calorific value of dried EFB usually between 16 and 18 MJ/kg, depending on moisture content and treatment method. This value is similar to that of other agricultural biomass fuels (Ahmad et al., 2016).

Several technologies have been used to convert EFB into practical energy forms, including: 1) Direct combustion in biomass boilers for steam and power generation (Chiew et al., 2013; Booneimsri et al., 2018; Maulana et al., 2016), 2) Pyrolysis to create bio-oil, biochar, and syngas (Harsono et al., 2013; Al-Maari et al., 2025; Rey et al., 2025; Unsomsri et al., 2026), and 3) Gasification to produce synthesis gas (H_2, CO) for power or fuel generation (Ismail et al., 2017; Silva et al., 2026; Al-Muraisy et al., 2025; Chuayboon et al., 2023; Detchusananard et al.,2022) .

In co-firing applications, EFB can be combined with other biomass fuels like palm kernel shell (PKS) or agricultural residues to improve its combustion properties and reduce emissions (Rusdianasari et al., 2023). The lower sulfur and nitrogen levels in EFB lead to reduced SO_2 and NO_x emissions, making it an eco-friendly option for biomass energy systems (Harahap et al., 2023). Additionally, EFB can be pelletized or briquetted to enhance handling, energy density, and storage, thus increasing its commercial potential as a renewable solid fuel.

2.3 Palm Kernel Shell

Palm Kernel Shell (PKS) is a hard, fibrous byproduct of palm oil extraction. As a solid biomass residue, PKS is considered one of the most promising renewable energy sources in tropical countries like Indonesia and Malaysia due to its high availability, high energy value, and low ash content (Handaya et al., 2022; Padavala et al., 2024; Alfian et al., 2026).

PKS contains more than 50% carbon, low moisture content (8 to 12% after drying), low ash content (around 1.5 to 2%), and a higher calorific value (HHV), which is around 18 to 21 MJ/kg. This calorific value is comparable to sub-bituminous coal (Sulaiman & Abdullah, 2011; Junga et al., 2020). Due to these properties, PKS is widely used in industrial boilers for steam generation. PKS is also used in coal-fired power plants to reduce dependence on fossil fuels and emissions (Varol et al., 2010). Furthermore, PKS is increasingly common in international biomass fuel trade, particularly between Indonesia and Japan, Korea, and Europe.

PKS can perform well in thermochemical conversion processes such as combustion, gasification, and pyrolysis. PKS combustion produces lower sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions compared to coal. This is due to the relatively low sulfur (0.07%) and nitrogen (0.47%) contents (Harahap et al., 2023). The carbon content helps maintain stable combustion, while volatiles support ignition and flame stability. Furthermore, torification or pelletization can increase the energy capacity of PKS, making it more suitable for large-scale energy applications (Junga et al., 2020; Abdul Halim et al., 2020; Sambeth et al., 2022).

2.4 Comparative Analysis and Theoretical Framework of Biomass Blending

Although cocopeat, empty fruit bunch (EFB), and palm kernel shell (PKS) have been widely investigated individually, a systematic comparative synthesis across these materials remains limited. Table-based comparative analyses in previous studies show that PKS generally exhibits the highest calorific value (18–21 MJ/kg) and lowest ash content (1.5–2%) (Junga et al., 2020; Sulaiman & Abdullah, 2011), making it suitable for stable boiler combustion. In contrast, EFB has moderate calorific value (16–18 MJ/kg) but relatively high ash content (up to 10%) and higher nitrogen content, which may increase NO_x formation (Ahmad et al., 2016; Harahap et al., 2023). Cocopeat, particularly in raw form, contains very high moisture (often >70%), significantly reducing its effective heating value unless dried or pelletized (Alamsyah et al., 2016; Borel et al., 2021). These differences suggest that blending these materials may balance moisture, ash, and carbon content, potentially creating synergistic combustion behavior.

However, prior literature largely discusses these materials separately without integrative evaluation of their combined thermochemical performance. Most combustion studies focus on single-fuel characterization or binary blends, with limited attention to ternary biomass systems for boiler-scale applications (Chiew et al., 2013; Booneimsri et al., 2018). Furthermore, calorific value reporting varies across studies due to differences in moisture basis (as-received vs dry basis), creating inconsistencies in comparative assessment. Boiler-scale challenges such as slagging, fouling, ash melting behavior, and alkali interaction are also not consistently addressed, particularly for EFB-rich blends which may increase ash-related operational risks (Uche et al., 2015; Vega et al., 2019).

From a combustion theory perspective, biomass blending is based on several thermochemical principles. First, moisture balancing improves ignition stability and reduces energy losses from water evaporation. Second, ash interaction effects may either reduce or intensify slagging depending on mineral composition synergy. Third, blending high-carbon PKS with higher-volatile biomass like EFB or cocopeat may enhance flame stability and combustion efficiency. Co-firing theory also suggests that appropriate blending can reduce emission precursors by diluting nitrogen- or sulfur-containing components (Harahap et al., 2023). Despite this theoretical potential, limited research quantitatively evaluates how optimized ternary blending affects both calorific performance and emission formation in industrial boiler conditions.

Emission characteristics in biomass combustion have been studied, particularly for SO_2 and NO_x reduction compared to coal (Varol et al., 2010; Harahap et al., 2023). PKS typically produces low SO_2 emissions due to low sulfur content (up to 0.07%), while EFB's higher nitrogen fraction may increase NO_x formation (Vega et al., 2019). However, previous studies rarely provide integrated emission modeling based on ultimate analysis combined with energy output estimation. In addition, particulate matter (PM), CO, and CO_2 emissions are often discussed qualitatively without systematic quantification for mixed biomass fuels. Few studies explicitly relate emission factors to boiler operational feasibility or national environmental standards.

Recent studies (2020–2025) have increasingly emphasized biomass thermochemical characterization and emission optimization strategies (Junga et al., 2020; Handaya et al., 2022; Harahap et al., 2023; Setiawan et al., 2025; Vieira et al., 2024). Nevertheless, most of these works focus on palm-based residues only and do not incorporate cocopeat as part of a multi-biomass optimization framework. Moreover, limited research addresses optimized cocopeat–EFB–PKS ternary mixtures specifically for industrial boiler applications in Indonesia, where fuel substitution feasibility must consider calorific value, ash behavior, emission estimation, and steam production performance simultaneously.

Therefore, the research gap identified in the literature is the absence of a systematic and comparative evaluation of optimized ternary cocopeat–EFB–PKS mixtures that integrates proximate and ultimate analysis, calorific performance comparison, emission estimation (CO_2, SO_2, NO_2), and boiler-scale steam production modeling. Addressing this gap is essential to scientifically justify blending strategies and enhance the sustainable utilization of underexploited coconut and palm biomass residues.

3. Research Methods

Research methods in this study can be seen in Figure 1.

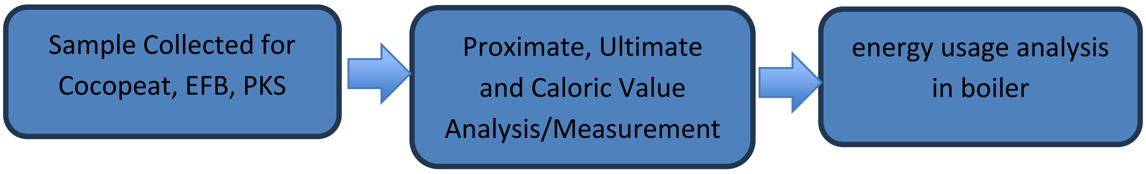


Fig. 1. Research Methodology

3.1. Sample Collected for Cocopeat, EFB and PKS.

At this initial stage, biomass samples of cocopeat and empty fruit bunch (EFB) are collected. These samples are sourced from relevant agricultural or industrial sites, such as coconut processing facilities or palm oil mills. The primary data was cocopeat blends which prepared by natural sun-drying to reduce its inherent moisture content prior to blending. The material was spread in a thin layer and exposed to direct sunlight for approximately 2–3 days under ambient outdoor conditions (average daytime temperature 30–33 °C) until reaching relatively stable mass. The dried cocopeat was then manually homogenized and blended with EFB. All primary biomass samples (BCO, EFB, and PKS) were milled and sieved to pass through a 60-mesh sieve to ensure uniform particle distribution prior to analysis. For blended samples, components were homogenized to ensure even mass distribution. The samples are 50% cocopeat blends to 50% EFB (BCO), 100% EFB (EFB), and 100% PKS (PKS). The blending sample was selected based on preliminary evaluation and literature suggesting balanced moisture and volatile content (Aji et al. 2022; Setiawan et al. 2025). Moreover, the secondary data were Pelletized cocopeat (PECO) characteristics that adopted from Aji et al. (2022). No pelletization, drying, or additional experimental treatment of PECO was conducted in the present study. The reported proximate and calorific value data were used as secondary input parameters for blending and performance modeling. The purpose of this stage is to provide raw materials for fuel characterization and energy analysis.

3.2. Proximate, Ultimate and Caloric Value Analysis

Laboratory experimental work consist of collected samples undergo proximate and ultimate analyses in accordance with ASTM (American Society for Testing and Materials) standards. Moisture content, ash content, volatile matter, fixed carbon (by difference) were determined in accordance with ASTM D3173, ASTM D3174, ASTM D3175, and ASTM D3172 standards, respectively, while the higher heating value (HHV) was measured following ASTM D5865. Proximate Analysis determines: Moisture content, ash content, carbon. Ultimate Analysis identifies elemental composition: Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S), Oxygen (O). The purpose of this stage is to assess the fundamental fuel properties and combustion behavior of cocopeat, EFB, and PKS. Following the compositional analysis, the calorific value (or heating value) of each biomass. This value indicates the amount of energy that can be released during complete combustion. Elemental composition (C, H, N, S, and O) was estimated based on previously reported ultimate analysis data from relevant literature sources. These values were used as input parameters for stoichiometric emission modeling and energy balance calculations. The purpose of this stage is to quantify the energy potential of cocopeat, EFB, and PKS as alternative solid fuels.

3.3. Calorific Value Measurement

The higher heating value (HHV) of the biomass samples was determined using a Parr 6200 Oxygen Bomb Calorimeter under controlled laboratory conditions. Prior to measurement, the instrument was calibrated using a certified benzoic acid standard to ensure accuracy and reliability of the calorific value results. All tests were conducted at ambient laboratory conditions with a temperature of 25 ± 2 °C and atmospheric pressure. These controlled conditions ensured stable combustion within the calorimetric chamber and minimized environmental influence on the measurement accuracy.

3. 4. Energy Usage Analysis in Boiler

Performance modeling was conducted using mass–energy balance calculations based on ultimate analysis results. Emission estimation was derived stoichiometrically from elemental composition (C, N, S), while steam production capacity was calculated using boiler efficiency assumptions and thermodynamic energy conversion principles. All calculations were implemented using spreadsheet-based computational analysis. This evaluation included estimating the thermal energy output of biomass fuel, calculating fuel efficiency in generating steam, and comparing combustion performance with practical applications in industrial-scale boilers. The objective of this phase was to evaluate the feasibility of utilizing cocopeat, EFB, and PKS as renewable fuels in a biomass boiler.

4. Results and Discussions

4.1 Results

4.1.1. Analysis in Biomass Fuel Characteristics

The biomass fuels used in this study were derived from cocopeat, PKS, and EFB. Pellet cocopeat (PECO) also compared to this analysis taken from previous study (Aji et al., 2022; Alamsyah et al., 2016). The resulting characteristics can be seen in Table 1. The table summarizes moisture content, ash content, hydrogen, carbon, oxygen, nitrogen, sulfur, and calorific value for BCO, PECO, EFB, and PKS.

Table 1 - Biomass Fuel Characteristics

Component (%-mass)	**BCO**	**PECO (Aji et al., 2022; Alamsyah et al., 2016)**	**EFB (Setiawan et al., 2025)**	**PKS (Setiawan et al., 2025)**
Moisture	31.35%	11.92%	8.56%	8.54%
Ash	4.61%	4.64%	10.13%	1.73%
Sulphur	0%	0.05%	0.05%	0.07%
Hydrogen	4.12%	5.8%	6.32%	5.81%
Carbon	22.39%	47.5%	44.21%	51.22%
Oxygen	36.65%	29.59%	26.93%	32.16%
Nitrogen	0.89%	0.5%	3.80%	0.47%
Caloric Value (MJ/kg)	6.9	17.14	11.88	19.62

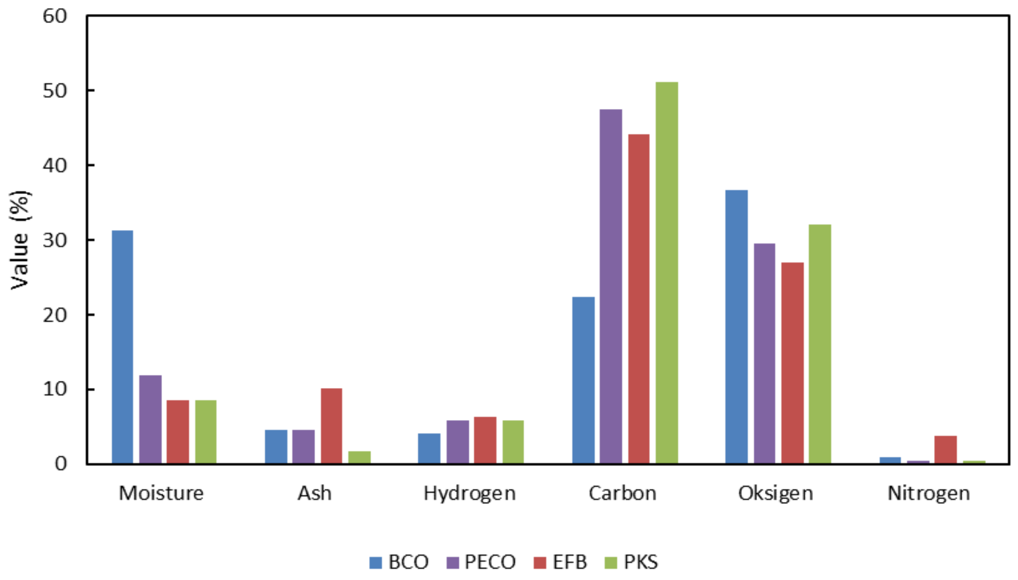


Fig. 2. Comparison from Biomass Characteristics

Table 1 shows that PKS exhibits the highest carbon content (51.22%) and the lowest ash content (1.73%) among the evaluated fuels. In contrast, EFB has a higher ash content (10.13%) and relatively higher nitrogen content compared with other biomass fuels. The moisture content of BCO is significantly higher than that of PECO, EFB, and PKS, indicating the influence of natural drying conditions during preparation.

The calorific value varies significantly across the fuels. PKS shows the highest heating value (19.62 MJ/kg), followed by PECO (17.14 MJ/kg), EFB (11.88 MJ/kg), and BCO (6.9 MJ/kg). The higher calorific value of PKS can be attributed to its higher carbon content and lower ash fraction, which enhances the combustible portion of the fuel. These results indicate that PKS has superior fuel properties compared to other biomass fuels in terms of energy density and combustion cleanliness.

Table 2 - Comparison of Energy Properties Between Fuels and Coal

Fuel Type	Carbon (%)	Ash (%)	Moisture (%)	Caloric Value (MJ/kg)
BCO	22.39	4.61	31.35	6.9
PECO (Aji et al., 2022; Alamsyah et al., 2016)	47.5	4.64	11.92	17.14
EFB (Setiawan et al., 2025)	44.21	10.13	8.56	11.88
PKS (Setiawan et al., 2025)	51.22	1.73	8.54	19.62
Sub-bituminous Coal (Liew et al, 2018; Altawell, 2021; Viswanathan, 2017)	70-76	5-15	15-30	19-27
Bituminious Coal (Liew et al, 2018; Viswanathan, 2017)	70-86	5-20	2-15	24-23

Figure 2 shows a graph comparing the characteristic values of 50% cocopeat (BCO), Pelet cocopeat (PECO), EFB, and PKS. The analysis can be explained as follows.

Table 2 presents a comparison of key fuel properties between the evaluated biomass fuels (BCO, PECO, EFB, and PKS) and conventional coal fuels. The comparison includes carbon content, ash content, moisture content, and calorific value. The results indicate that PKS exhibits the highest carbon content (51.22%) and the lowest ash content (1.73%) among the biomass fuels, resulting in the highest calorific value (19.62 MJ/kg). In contrast, BCO shows significantly lower energy performance due to its high moisture content (31.35%) and low carbon fraction, leading to a calorific value of only 6.9 MJ/kg. PECO demonstrates a relatively high calorific value (17.14 MJ/kg), which is comparable to the lower range of sub-bituminous coal (19–27 MJ/kg). Meanwhile, EFB exhibits moderate energy potential but is limited by its higher ash content (10.13%), which may affect combustion efficiency.

Overall, the results show that biomass fuels, particularly PKS and PECO, approach the energy characteristics of low-rank coal, indicating their potential as alternative fuels in boiler applications.

The increase in calorific value with higher PKS fraction can be explained by its higher carbon content and lower ash fraction compared with cocopeat and EFB. Biomass fuels with higher fixed carbon typically produce higher heating values due to greater combustible material available during oxidation reactions (Noushabadi et al., 2021; Zhao et al., 2025).

In moisture content, high moisture can reduce combustion efficiency because some energy is wasted evaporating the water (Uche et al., 2015). BCO tends to be moister than PECO, EFB and PKS, requiring additional drying before use as fuel. On the other hand, PKS also has lower moisture content, which reduces energy losses associated with water evaporation during combustion. In contrast, EFB and cocopeat contain higher moisture, which decrease the effective energy released during combustion.

In analyzing ash content, high ash levels can potentially clog the grates, reduce combustion efficiency, and increase boiler cleaning requirements. EFB has the highest ash content compared to BCO, PECO and PKS, so excessive use can accelerate boiler scale formation. PKS excel due to their very low ash content, resulting in cleaner combustion (Nurdin et al.,2025).

In the sulfur analysis, it was found that BCO, PECO, EFB and PKS were all low in sulfur, so they were safe from excess SO_2 emissions. Analysis of hydrogen content, it can be seen that the H value affects the formation of water vapor during combustion. The hydrogen values for BCO, PECO, EFB, and PKS are nearly identical for all three. Moreover, Table 1 PKS has the highest C making higher caloric value than BCO, PECO and EFB. BCO is smaller in carbon, so the caloric value is the smallest. Furthermore, the result of nitrogen (N), EFB has a high nitrogen value compared to BCO and PKS so it has the potential to increase NOx during combustion (Vega et al., 2019).

4.1.2. Effect of Biomass Blending on Caloric Value

To obtain high calorific value, it is necessary to mix between cocopeat, EFB and PKS fuel. In this study, mixing between BCO, PECO, EFB and PKS. Six blending scenarios were evaluated by varying the proportions of cocopeat (PECO or BCO), EFB, and PKS. This mixing composition was derived from previous research (Setiawan et al., 2025), which showed that a good mixing ratio is 30% EFB. Therefore, the blending process is carried out to adjust the fuel composition. The compositions can be seen in Table 3 below:

Table 3 - Composition of Mixing

Scenario	Mixing Composition	Cocopeat (PECO/BCO)	EFB	PKS	Caloric Value (MJ/kg)
1	30% PECO, 50% EFB ,20% PKS	0.30	0.50	0.20	15.01
2	20% PECO, 40% EFB, 40% PKS	0.20	0.40	0.40	16.03
3	10% PECO, 30% EFB, 60% PKS	0.10	0.30	0.60	17.05
4	30% BCO, 50% EFB ,20% PKS	0.30	0.50	0.20	11.93

5	20% BCO, 40% EFB ,40% PKS	0.20	0.40	0.40	13.98
6	10% BCO, 30% EFB, 60% PKS	0.10	0.30	0.60	16.03

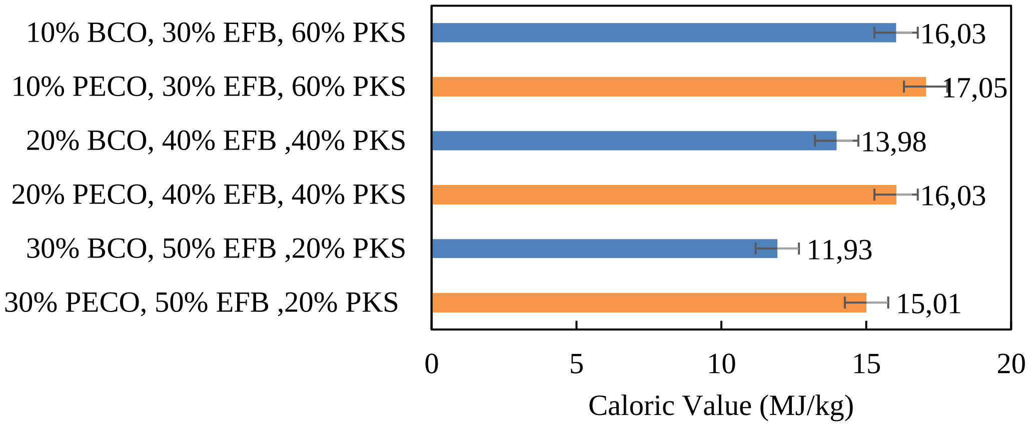


Fig. 3. Relationship Between Composition Biomass Mixtures and Calorific Value

As can be seen in Table 3, the highest caloric value is 17.05 MJ/kg in scenario 3 (10% PECO, 30% EFB, 60% PKS) and scenario 6 (10% BCO, 30% EFB, 60% PKS) with 16.03 MJ/kg. Moreover, Figure 3 shows that increasing the PKS fraction consistently increases the calorific value of the mixture. Scenario 3 (10% PECO, 30% EFB, 60% PKS) produced the highest calorific value of 17.05 MJ/kg, while Scenario 1 (30% PECO, 50% EFB, 20% PKS) produced a lower value of 15.01 MJ/kg. Similarly, mixtures containing BCO exhibit lower calorific values compared with those containing PECO due to higher moisture content and lower carbon concentration in BCO. This trend can be explained by the higher carbon content and lower ash fraction of PKS compared with EFB and cocopeat. Higher carbon content increases the combustible energy stored in the fuel, while lower ash reduces inert material that does not contribute to heat release during combustion.

The calorific value of 17.05 MJ/kg is considered relatively high compared with several agricultural residues such as rice husk (13–15 MJ/kg), bagasse (15–17 MJ/kg), and corn cob (16–18 MJ/kg), indicating competitive energy potential for industrial boiler applications (Vega et al., 2019; Uche et al., 2015; Ahmad et al., 2016; Vieira et al., 2024; Junga et al., 2020; Bemgba et al., 2014).

It can be concluded that the higher the PKS fraction, the higher the calorific value of the mixture which represents a balance between energy density and biomass waste utilization.

4.1.3. Estimated Emission from Biogas Combustion

The estimated emissions of CO_2, SO_2, and NO_2 for each mixture scenario are presented in Table 4. Emission values were calculated based on elemental composition using stoichiometric combustion equations. The main exhaust gas emissions were estimated, namely carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). This estimation is based on the final elemental content of each fuel: Carbon (C), Sulfur (S), and Nitrogen (N).

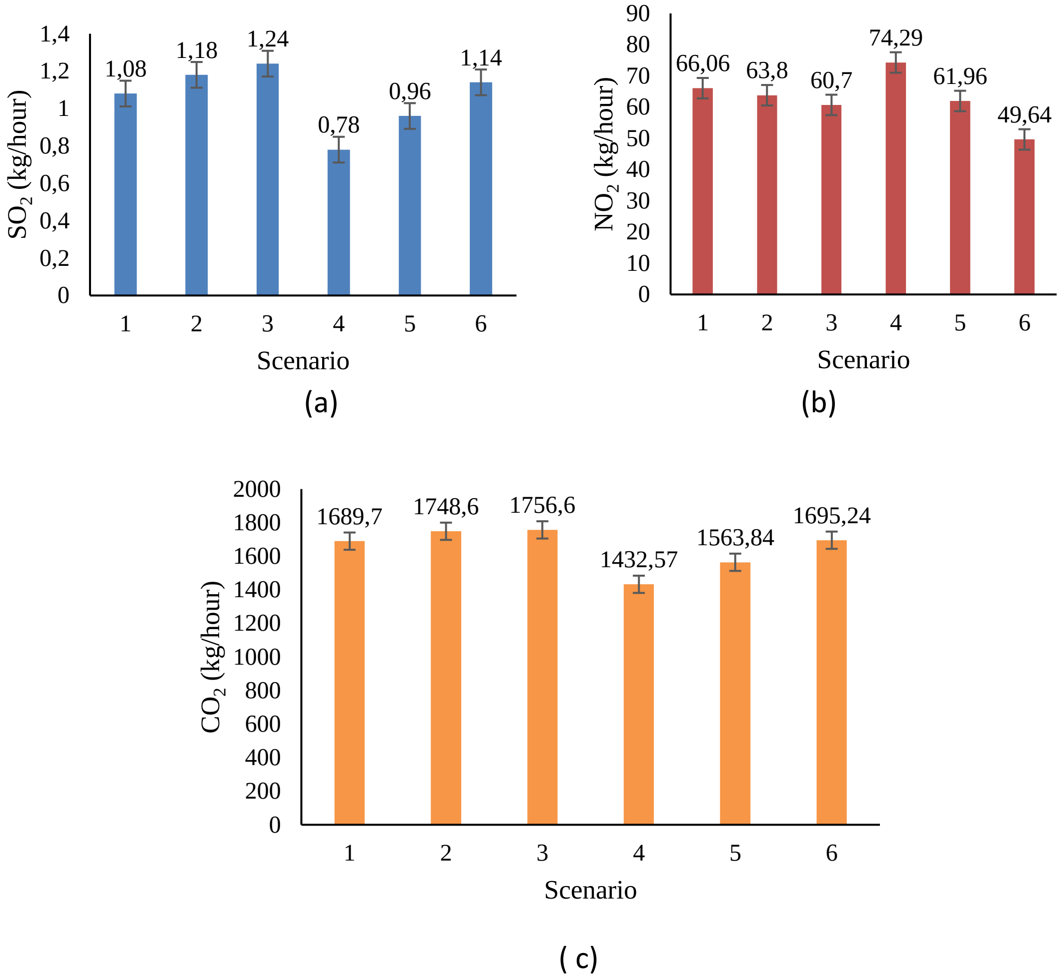
Assume that the contribution of C, N, and S elements from 1000 kg of mixed fuel, and calculate the estimated gas emissions (Koppejan & Van Loo, 2008):

$$CO_2 = C(kg) \times 44/12 \quad (C + O_2 \rightarrow CO_2) \tag{1}$$
$$SO_2 = S\ (kg) \times 32/64 \quad (S + O_2 \rightarrow SO_2) \tag{2}$$
$$NO_2 = N(kg) \times 46/14 \quad (N + O_2 \rightarrow NO_2) \tag{3}$$

Estimated emissions per 1000 kg of biomass fuel:

Table 4 - Estimated Emissions of Biomass Fuel

Scenario	**Compositions**	**CO_2 (kg/hour)**	**SO_2 (kg/ hour)**	**NO_2 (kg/ hour)**
1	30% PECO, 50% EFB ,20% PKS	1689.7	1.08	66.06
2	20% PECO, 40% EFB, 40% PKS	1748.6	1.18	63.8
3	10% PECO, 30% EFB, 60% PKS	1756.6	1.24	60.7
4	30% BCO, 50% EFB ,20% PKS	1432.57	0.78	74.29
5	20% BCO, 40% EFB ,40% PKS	1563.84	0.96	61.96
6	10% BCO, 30% EFB, 60% PKS	1695.24	1.14	49.64



(a) (b)

(c)

Fig. 4. Estimated Emissions from Biomass Fuel; (1) SO_2; (2) NO_2; and (c) CO_2

As can be seen in Figure 4 that scenario 6 (10% BCO, 30% EFB, 60% PKS) has estimated lower NO_2 emissions compared to others. While Scenario 4 (30% BCO, 50% EFB, 20% PKS) produced the highest NO_2 emissions. Moreover, estimated CO_2 emissions are still higher than scenario 4 and 5, but the emissions are still low and still within safe limits. Moreover, scenario 4 (30% BCO, 50% EFB ,20% PKS) has the highest of NO_2 emissions, but lower in SO_2 emissions. Nevertheless, all SO_2 emissions in this scenario are very small and still at a very safe level.

4.1.4. Estimation of Steam Production from Fuel Mixture

The aim of this estimation is to convert the energy from the combustion of the BCO, PECO, EFB, PKS mixture into the amount of steam that can be produced by the boiler. Steam production estimates based on biomass calorific value and assumed boiler efficiency are presented in Table 4. A boiler efficiency of 75% and working pressure 21 barg were adopted to represent typical operational conditions of industrial biomass-fired boilers, where efficiency generally ranges between 70% and 85% depending on fuel properties, excess air ratio, and system design (Koppejan & Van Loo, 2008; Saidur et al., 2010; Setiawan et al., 2025). The selected value reflects a moderate and realistic efficiency for small-to-medium scale biomass boiler systems.

Assumptions:

Boiler efficiency: 75% ($\eta = 0.75$)

Energy to produce 1 kg of steam at 21 barg: approximately 2.75 MJ/kg

Table 4 - Estimation of Steam Production

Scenario	Compositions	Gross Energy (MJ/hour)	Effective Energy (MJ/hour)	Steam Production (kg/hour)
1	30% PECO, 50% EFB ,20% PKS	15010	11257.5	4093.64
2	20% PECO, 40% EFB, 40% PKS	16030	12227.25	4446.27
3	10% PECO, 30% EFB, 60% PKS	17050	12787.5	4650.00
4	30% BCO, 50% EFB ,20% PKS	11930	8947.5	3253.64
5	20% BCO, 40% EFB ,40% PKS	13980	10485	3812.73
6	10% BCO, 30% EFB, 60% PKS	16030	12022.5	4371.82

As can be seen in Table 4, scenario 3 (10% PECO, 30% EFB, 60% PKS) produced the highest steam generation potential of 4650 kg/hour, followed by scenario 6 (10%BCO, 30% EFB, 60% PKS) with 4371.82 kg/hour. The scenario 3 is the best choice for using pellet cocopeat (10% PECO, 30% EFB, 60% PKS) because it can minimize NO_2 emissions and also has high steam production. Moreover, scenario 6 is the best choice for mixing cocopeat (10% BCO, 30% EFB, 60% PKS) because it has high production steam and lower NO_2 emissions. This result has the same to other study that the composition of EFB is 30% has the best composition for use in boilers to produce low emissions compared to other compositions (Harahap et al., 2023).

4.2. Discussions

4.2.1. Influence of Biomass Composition on Combustion Performance

The increase in calorific value with higher PKS fraction can be explained by its higher carbon content and lower ash fraction compared with cocopeat and EFB. Biomass fuels with higher fixed carbon typically produce higher heating values due to greater combustible material available during oxidation reactions (Racero et al., 2024; Yin, 2011). PKS also has lower moisture content, which reduces energy losses associated with water evaporation during combustion. In contrast, EFB and cocopeat contain higher moisture and ash fractions, which decrease the effective energy released during combustion.

4.2.2. Relationship Between Nitrogen Content and NO_2 Formation

The estimated NO_2 emissions show a clear relationship with the nitrogen content of the fuel mixtures. EFB contains higher nitrogen compared with PKS and cocopeat, which contributes to increased NOx formation during combustion. However, it should be noted that the emission estimation in this study assumes complete conversion of nitrogen into NO_2 based on stoichiometric calculations. In real combustion systems, nitrogen conversion to NOx depends on several factors such as combustion temperature, excess air ratio, and residence time (Roeder et al., 2025). Therefore, the emission values presented in this study was interpreted as theoretical maximum estimates rather than actual measured emissions.

4.2.3. Comparison with Other Biomass Fuels

The calorific value obtained for the optimal mixture (17.05 MJ/kg) is comparable with several biomass fuels reported in the literature. For example, typical calorific values for EFB range between 16–18 MJ/kg, while cocopeat pellets range from 15–18 MJ/kg depending on moisture content. PKS generally exhibits calorific values between 18–21 MJ/kg, which are close to low-rank coal fuels. This indicates that the optimized biomass mixture evaluated in this study has competitive energy density for industrial boiler applications.

4.2.4. Comparison with Coal and Implications for Boiler Application

The comparison between biomass fuels and coal, as shown in Table 2, provides important insights into the feasibility of biomass substitution in industrial boiler systems. Coal typically has higher carbon content (70–86%) and calorific value (19–27 MJ/kg), making it a highly energy-dense fuel. However, PKS exhibits a calorific value of 19.62 MJ/kg, which is very close to the lower range of sub-bituminous coal, indicating strong potential as a renewable substitute.

The optimized biomass mixture identified in this study (17.05 MJ/kg) falls within the range of commercial biomass fuels and approaches the lower boundary of coal energy content. This demonstrates that appropriate blending of cocopeat, EFB, and PKS can significantly enhance the energy density of biomass fuels, making them suitable for boiler applications.

In addition to calorific value, ash content plays a critical role in boiler operation. EFB shows relatively high ash content (10.13%), which may increase the risk of slagging and fouling in heat transfer surfaces. In contrast, PKS has very low ash content (1.73%), contributing to cleaner combustion and reduced maintenance requirements. Therefore, increasing PKS fraction not only improves energy output but also enhances combustion cleanliness.

Moisture content is another important parameter affecting combustion efficiency (Gute et al., 2022; Xu et al., 2026). High moisture levels in BCO (31.35%) significantly reduce its effective calorific value due to energy losses associated with water evaporation. This explains the lower performance of BCO-based mixtures compared to PECO-based mixtures.

From a practical perspective, although biomass fuels generally have slightly lower energy density than coal, their renewable nature and lower sulphur content provide environmental advantages. However, the substitution of coal with biomass requires careful optimization of fuel composition to balance calorific value, emission characteristics, and operational stability.

The results indicate that PKS-dominant biomass blends can achieve energy densities approaching fossil fuels, while maintaining lower ash and sulfur content, which is advantageous for sustainable boiler operation.

4.2.5. Trade-Off Between Energy Output and Emission

Although higher PKS fractions increase calorific value and steam production potential, they also increase CO_2 emissions due to higher carbon content. Conversely, mixtures containing higher EFB fractions may increase NOx formation due to higher nitrogen content. Therefore, biomass blending optimization must balance energy efficiency and emission reduction simultaneously.

5. Conclusion

Palm Kernel Shell (PKS) has the highest carbon content (51.22%) and the lowest ash content (1.73%), making it the most superior biomass fuel candidate in terms of calorific value and combustion residue. Cocopeat has a very high initial moisture content (up to 82.79%), but after the palletization process and mixed with EFB, it becomes a combustible fuel with a competitive calorific value. The optimal composition of the cocopeat pellet mixture is 10% PECO, 30% EFB, 60% PKS, has a high calorific value, namely 17.05 MJ/kg. In addition, the NO_2 emission level is also lower and can produce high steam in the boiler, which is around 4650.00 kg/hour. In addition, the cocopeat mixture (BCO), namely 10% BCO, 30% EFB, and 60% PKS, has a low NO_2 emission value and can produce high steam in the boiler, which is around 4371.82 kg/hour. This shows that cocopeat can be used as a new fuel if mixed with PKS and EFB, so that the use of coconut waste can be maximized and can reduce emissions to the environment. From a practical perspective, the obtained calorific value (17.05 MJ/kg) and steam production capacity indicate that the proposed biomass mixtures are technically feasible for industrial-scale boiler applications, particularly as partial substitutes for low-rank coal. However, it should be noted that the emission results are based on stoichiometric estimation and require further experimental validation under real combustion conditions. Future research should focus on experimental combustion testing using real boiler systems, detailed emission measurements including NOx and particulate matter, and evaluation of combustion efficiency and long-term operational impacts such as slagging and fouling. In addition, techno-economic analysis and life cycle assessment (LCA) are recommended to evaluate the sustainability and economic feasibility of large-scale implementation.

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