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A comparative analysis of the thermochemical properties and gasification efficiency of palm kernel shell and coal for clean energy applications

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ABSTRACT

The growing global energy demand has driven the exploration of alternative, more environmentally friendly energy sources to replace fossil fuels. Palm kernel shell (PKS), a biomass waste, and coal, a primary fossil fuel, have distinct thermochemical characteristics, which present both challenges and opportunities in gasification processes. This study aims to analyze and compare the thermochemical properties of both feedstocks, including proximate and ultimate analyses, gasification efficiency, calorific values, and syngas composition. The research involved raw material characterization, gasification in a reactor, and gas composition analysis using gas chromatography. Results indicated that PKS has a significantly higher volatile matter content (68.31% adb) compared to coal (41.75%), resulting in a higher H_2/CO ratio (24.19% at 500 °C). Conversely, coal exhibited a higher gross calorific value (HHV) at lower temperatures, reaching 25.38 MJ/Nm³ at 350 °C. However, the carbon conversion efficiency (%CCE) of PKS remained more stable at moderate temperatures, achieving 89.19% at 350 °C, compared to coal, whose efficiency dropped drastically to 7.07% at 650 °C. In conclusion, PKS demonstrates significant potential as an efficient and environmentally friendly renewable energy feedstock at moderate to high temperatures, and it could replace or complement coal in clean energy applications.

Keywords: palm kernel shell, coal, gasification, syngas composition, thermochemical properties.

INTRODUCTION

The growing global demand for sustainable energy has driven the exploration of alternative, more environmentally friendly energy sources to replace increasingly depleting fossil fuels (Holechek et al., 2022). Biomass, particularly palm kernel shell (PKS), has attracted attention as a renewable energy source abundant in palm oil-producing countries like Indonesia and Malaysia (Kaniapan et al., 2021). As an agricultural waste, PKS not only offers significant energy value but also contributes to carbon emission reduction and more sustainable waste management (Uchegbulam et al., 2022). Meanwhile, coal remains the primary fuel in the energy industry due to its high carbon content and superior calorific value (Cheng et al., 2024).

Gasification, as a thermochemical technology, holds great potential for converting biomass and coal into syngas rich in hydrogen (H_2) and carbon monoxide (CO), which can be used as fuel or chemical feedstocks (Maitlo et al., 2022). However, the chemical composition differences between PKS and coal create unique challenges and opportunities in the gasification process, including conversion efficiency, syngas characteristics, and emissions (Quintero-Coronel et al., 2022).

While biomass such as PKS has advantages as a renewable fuel, its thermochemical properties, such as high oxygen content and lower calorific value compared to coal, may impact gasification efficiency (Khan et al., 2024). Furthermore, much of the previous research has focused on a single feedstock type (biomass or coal) without directly comparing their thermochemical properties and gasification performance. This leaves room for more in-depth studies on how biomass like PKS can compete with or complement coal in energy applications (Zamri et al., 2022).

Recent research over the last five years has shown significant progress in biomass and coal studies for gasification applications. According to Zhang et al, the thermochemical properties of biomass for gasification have been outlined, but a direct comparison with coal has not been conducted (Zhang et al., 2021). Meanwhile, Li et al, analyzed the syngas composition from coal with catalyst use but did not include biomass in the feedstock mix (Li et al., 2021). Su et all, studied biomass gasification efficiency using metal-based catalysts but did not compare the results with coal gasification (Su et al., 2022). Other studies measured the H_2/CO ratio from biomass and coal gasification separately, without evaluating the impact on overall energy efficiency (Rosyadi et al., 2024). Despite numerous studies, a comprehensive comparison between biomass such as PKS and coal regarding thermochemical properties remains lacking.

Previous studies have not specifically compared the thermochemical properties (proximate and ultimate) between biomass, such as PKS, and coal in the context of gasification. Additionally, there has been no comprehensive integration of gasification performance data, such as carbon efficiency (%CCE), gas efficiency (%CGE), and high (HHV) and low (LHV) heating values, to evaluate the energy potential of both feedstocks. Research also remains limited in identifying how differences in gas composition (syngas) affect the energy applications of biomass and coal.

The novelty of this research lies in a comprehensive comparative analysis between PKS and coal, covering thermochemical properties, gasification efficiency, and syngas composition. This study also utilizes efficiency metrics such as %GC, %NGC, %CCE, and %CGE to quantitatively evaluate gasification performance, providing a more measurable approach to assess the energy potential of both feedstocks. Furthermore, the study offers new insights into how biomass, particularly PKS, can replace or complement coal in renewable energy applications.

The objective of this study is to analyze and compare the thermochemical properties of PKS and coal through proximate and ultimate data, to gain a deeper understanding of the characteristics of each feedstock. The research also aims to evaluate the gasification performance of both feedstocks based on efficiency parameters such as %CCE and %CGE, as well as the energy values produced (HHV and LHV). In addition, the study seeks to identify the syngas characteristics produced, such as the H_2/CO ratio, %GC, and %NGC, to understand the potential energy applications of each feedstock.

MATERIALS AND METHODS

Materials

This study involved two primary materials: coal and palm kernel shell. The coal used was sourced from PTBA Kertapati, South Sumatra, Indonesia, selected due to its characteristics being suitable for gasification needs in Indonesia. Meanwhile, the palm kernel shell utilized in this research was obtained from a CPO (Crude Palm Oil) industry located at Dermaga Pelabuhan Dalam, Tanjung Api-Api, Banyuasin Regency, South Sumatra. The selection of palm kernel shell was based on its abundant availability and its potential as an alternative energy source. Proximate and ultimate analyses in this study were conducted using standard ASTM methods at the Sucofindo Laboratory, Palembang Branch, to ensure the accuracy and consistency of results. The analytical instrument employed was Gas Chromatography (GC-Shimadzu-2014) in the Laboratory Department of PT Pupuk Sriwidjaja Palembang.

Methods

The process begins with raw material preparation, which includes crushing, washing, and drying, followed by a characterization analysis through proximate and ultimate testing. The prepared raw materials are then fed into the gasification reactor along with steam, producing syngas. The generated syngas is analyzed using GC to determine its composition. Additionally, the calorific value and gasification efficiency are calculated to evaluate the performance of the process. This diagram demonstrates a systematic approach to utilizing biomass waste and coal as alternative energy sources.

The flow diagram illustrates the processing of raw materials, namely palm kernel shell and coal, to produce syngas via gasification. The first stage involves raw material preparation, where palm kernel shell is crushed into small sizes (0.5 mm or 5 mesh) to increase the surface area for reaction. Next, both palm kernel shell and coal are washed with aquadest to remove impurities and contaminants. After washing, the materials are dried under sunlight for two days to reduce moisture content, which is crucial for improving gasification efficiency.

Once the raw materials are ready, they undergo characterization through proximate and ultimate analyses. Proximate analysis determines moisture, ash, volatile matter, and fixed carbon content, while ultimate analysis identifies the main elemental composition, including carbon, hydrogen, oxygen, sulfur, and nitrogen. This information ensures the quality of raw materials before proceeding to gasification.

The next stage is the gasification process, where the palm kernel shell and coal are fed into the reactor along with steam. This process generates syngas, a mixture of gases such as CO, H_2, and CH_4.

The produced syngas is then analyzed using gas chromatography to determine its detailed composition. Additionally, the calorific value of syngas is calculated to assess the energy produced, and gasification efficiency is evaluated to determine the performance of the process. These steps optimize the gasification process to produce high-quality syngas with maximum efficiency

Anaysis data

Identify the components of the syngas produced using the gas chromatography method. Then, calculate the process efficiency, heating value, and gasification process efficiency.

The %GC can be calculated using the following formula:

$$\%GC\left(\frac{W_{initial}-W_{residual}}{W_{initial}}\right)\times 100 \tag{1}$$

where: $W_{initial}$ –initial weight of the biomass feedstock (grams), $W_{residual}$ – weight of the residual solid (char/ash) after the gasification process (grams).

The general formula for calculating %NGC is:

$$\%NGC = 100 - \%GC \tag{2}$$

where: weight of gas produced; the total mass of gaseous products generated during the process, weight of residues; the leftover solids, such as char or ash, initial biomass weight; the total weight of the feedstock before gasification.

The formula for calculating the higher heating value (HHV) of a fuel is:

$$HHV = H_2.HHV_{H2} + CO.HHV_{CO} + CH_4.HHV_{CH4} \tag{3}$$

where: the HHV values for each gas (in MJ/m³) are: $HHV_{H2} = 12.75$, $HHV_{CO} = 12.63$, and $HHV_{CH4} = 39.82$.

The general formula for calculating the lower heating value (LHV) is:

$$LHV = HHV - (h_{vapor} x m_{H2O}) \tag{4}$$

where: h_{vapor} is the latent heat of vaporization (the energy required to convert water into vapor), m_{H2O} is the mass of water formed during combustion.

Carbon conversion efficiency (%CEE) is used to determine the efficiency of converting carbon in biomass into gases such as CO and H_2, using the following formula:

$$\%CEE = \left(\frac{Carbon\ in\ Gas}{Carbon\ in\ Biomass}\right)\times 100 \tag{5}$$

where: *Carbon in Gas* refers to the amount of carbon present in the gas products (e.g., CO, H_2), while *Carbon in Biomass* represents the total carbon content in the biomass feedstock.

Cold gas efficiency (%CGE) measures the energy efficiency of syngas produced at low temperatures, with the formula:

$$\%CGE = \left(\frac{Energy\ in\ Syngas}{Energi\ in\ Biomass}\right)\times 100 \tag{6}$$

In this context, *Energy in Syngas* refers to the total energy content of the produced syngas (heating value of syngas), and *Energy in Biomass* is the total energy content of the biomass feedstock.

In this study, testing was conducted once for each parameter and variable measured due to limitations in resources and time. To enhance the analysis, a descriptive approach was employed, utilizing additional data sourced from relevant international literature and open-access materials. These data were used to evaluate trends and compare them with the experimental results, including gas composition, gasification efficiency, and HHV and LHV values. The descriptive analysis was conducted without making any inferential statistical claims. All data from the literature were processed and cited in accordance with their original sources.

RESULT AND DISCUSSION

Proximate and ultimate analysis

The comparison of proximate and ultimate characteristics between palm kernel shell and coal, including parameters such as moisture content, ash content, volatile matter, fixed carbon, calorific value, and elemental composition (carbon, hydrogen, nitrogen, and oxygen), is shown in Table 1. This data provides an overview of the potential of both materials as energy sources.

Proximate analysis

The proximate analysis results show that the total moisture content of coal is 23.76% (ar), significantly higher than that of palm kernel shell at 12.71% (ar). High moisture in coal reduces energy efficiency as more energy is consumed to evaporate water during gasification. In contrast, the lower moisture content in palm kernel shell makes it more suitable for gasification with higher energy efficiency. Research by Condori et al. (2024) supports that biomass with low moisture content produces better-quality syngas, with higher CO and H_2 content.

Palm kernel shell exhibits a much higher volatile matter content of 68.31% (adb) compared to coal at 41.75% (adb). This indicates that palm kernel shell decomposes thermally more readily, producing reactive gases like CO, CH_4, and H_2 more quickly during gasification. On the other hand, coal, while having lower volatile matter, shows a higher fixed carbon content of 42.97% (adb) compared to palm kernel shell at 18.29% (adb). High fixed carbon content in coal supports energy generation through the combustion of carbon into carbon monoxide over a longer period. (Ibrahim et al., 2024)

Palm kernel shell has significantly lower total sulfur (TS) content at 1.10% (adb) compared to coal at 0.78% (adb). This makes palm kernel shell more environmentally friendly as it produces lower emissions of sulfur oxides (SOx) and hydrogen sulfide (H_2S) during gasification. Research by Rey et al., (2024) emphasizes that biomass with low sulfur content produces cleaner syngas, making it more suitable for green energy applications.

Ultimate analysis

The ultimate analysis results reveal that coal has a carbon (C) content of 63.83%, much higher than palm kernel shell at 46.47%. The high carbon content in coal makes it more efficient in generating carbon monoxide (CO) in syngas, a key component for energy production in gasification-based systems. Conversely, the lower carbon content in palm kernel shell is offset by its significantly higher oxygen (O) content of 44.91% (adb) compared to coal at 24.73% (adb). This high oxygen content promotes the formation of hydrogen (H_2) during gasification, making palm

Table 1. Proximate and ultimate characteristics of palm kernel shell and coal

Parameter	Unit	Palm kernel shell	Coal
Total moisture (as received, ar)	%	12.71	23.76%
Proximate analysis (adb):			
- Moisture in the analysis	%	11.49	11.88
- Ash content	%	1.91	3.4
- Volatile matter	%	68.31	41.75
- Fixed carbon	%	18.29	42.97
- Total sulphur	%	1.10	0.78
Gross calorific value	kcal/kg	4359	6304
Ultimate analysis:			
- Carbon	%	46.47	63.83
- Hydrogen	%	5.94	6.02
- Nitrogen	%	0.67	1.09
- Oxygen	%	44.91	24.73

kernel shell more suitable for producing syngas with a higher H_2/CO ratio (Ashfaq et al., 2024a).

The hydrogen (H) content is nearly identical for both fuels, at 5.94% (adb) for palm kernel shell and 6.02% (adb) for coal. Hydrogen contributes directly to the formation of H_2 gas in syngas. However, the nitrogen (N) content in coal is higher at 1.09% (adb) compared to 0.67% (adb) in palm kernel shell. High nitrogen content in coal increases the risk of nitrogen oxide (NOx) emissions, which are harmful to the environment. On the other hand, the lower nitrogen content in palm kernel shell results in cleaner emissions during combustion or gasification.

Coal's sulfur (S) content of 0.78% (adb) is higher than palm kernel shell's 1.10% (adb). The lower sulfur content in palm kernel shell makes it a more eco-friendly fuel, minimizing hydrogen sulfide (H_2S) emissions in syngas.

In the gasification process, coal's high fixed carbon content generates syngas rich in carbon monoxide (CO), making it suitable for power generation and heavy industries requiring high energy. However, the higher sulfur and nitrogen content in coal increases the risk of harmful emissions, such as SO_x and NO_x, which can pollute the environment. Conversely, palm kernel shell's high volatile matter and oxygen content produce syngas with higher hydrogen (H_2) ratios, making it ideal for clean energy applications like hydrogen fuel. Its lower sulfur and nitrogen content also make it more environmentally friendly than coal. Research by Ashfaq et al. (2024) supports that biomass with high oxygen content produces syngas with a higher H_2/CO ratio, suitable for green energy technologies.

The effect of gasification temperature on the percentage of gas composition

The gasification of palm shell produces gas consisting of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2), under varying temperatures of 350–650 °C, measured through GC testing. Generally, an increase in temperature influences the chemical reactions taking place, including pyrolysis, reforming, and hydrocarbon decomposition reactions. The GC analysis results of palm kernel shell and coal are shown in Table 2.

Table 2 shows that hydrogen (H_2) reaches its maximum concentration at 500 °C, amounting to 24.19%, before decreasing significantly at temperatures between 600–640 °C. This indicates that 500 °C is the optimal temperature for H_2 production, likely derived from tar reforming and volatile compound reactions such as $CH_4 + H_2O \rightarrow CO + 3H_2$. The decline in H_2 at higher temperatures (> 500 °C) may occur due to oxidation or recombination reactions, such as water (H_2O) formation.

Methane (CH_4) content exhibits a high initial concentration at low temperatures (375 °C, 29.54%) but tends to decrease to 20.62% at 450 °C. The concentration then increases again to 25.82% at 640 °C, reflecting the decomposition of light hydrocarbon compounds at high temperatures,

Table 2. Gas composition from gasification of coal and palm kernel shel

Materials	Temperature	Sample code	Volume percentage (%)				
	(°C)		H_2	CO	CH_4	CO_2	N_2
PKS	350	TC-29	14.7224	0.0276	29.54	7.0242	8.9982
	400	TC-30	15.4071	0.0171	23.7789	6.7152	12.9735
	450	TC-31	22.4532	0.0138	20.6194	5.1182	6.9374
	500	TC-32	24.193	0.0184	19.9972	4.6254	10.5287
	550	TC-33	22.0922	0.0252	24.0566	8.3307	13.3291
	600	TC-34	13.9845	0.0123	18.3596	4.225	23.8542
	650	TC-35	2.5878	0.0029	25.8186	0.3885	35.5556
Coal	350	BB-1	1.4583	0.0465	53.2582	3.6248	5.4535
	400	BB-2	3.5365	0.0524	22.5094	7.5008	36.6336
	450	BB-3	9.5218	0.0405	15.2992	4.8541	0
	500	BB-4	14.9999	0.0383	22.0893	3.8453	13.5732
	550	BB-5	3.9031	0.0065	6.1678	1.0459	44.8531
	600	BB-6	6.6571	0.0003	8.8712	0.1625	32.3892
	650	BB-7	6.0107	0.0017	3.8397	0.6728	40.717

supported by pyrolytic decomposition and partial tar reforming reactions. Carbon dioxide (CO_2) content significantly decreases with increasing temperature, from 7.02% at 375°C to only 0.39% at 640 °C. This decline indicates the consumption of CO_2 in reactions such as the Boudouard reaction ($C + CO_2 \rightarrow 2CO$) and methane reforming ($CH_4 + CO_2 \rightarrow 2CO + 2H_2$), which convert CO_2 into other gases like CO and H_2.

Carbon monoxide (CO) remains minimal across all temperatures, with its highest concentration being only 0.0276% at 375 °C. This suggests that the partial oxidation of carbon into CO occurs minimally, likely due to reaction conditions unfavorable for significant CO formation. Meanwhile, inert gases such as nitrogen (N_2) and argon (Ar) show a sharp increase at higher temperatures, with N_2 reaching 35.56% at 640 °C. This occurs as the decomposition of organic material produces more non-reactive gases, while chemical reactions involving these gases are highly limited.

Overall, palm shell gasification demonstrates a complex dynamic, with temperature playing a crucial role in determining the composition of the produced gas. At moderate temperatures (450–550 °C), active reforming and pyrolysis reactions significantly generate H_2 and CH_4. However, at high temperatures (> 600 °C), the consumption of volatile compounds and the formation of inert gases become more dominant. Therefore, operational temperature optimization is essential to enhance gasification efficiency, particularly for maximizing hydrogen production as a high-energy fuel.

This study aligns with the findings of Rao et al. (2023), who reported that reforming reactions are more active at moderate temperatures, and Jagodzińska et al. (2021), who found that light hydrocarbon decomposition dominates at higher temperatures. The main mechanisms involved include initial pyrolysis, tar and methane reforming, the Boudouard reaction, and partial oxidation reactions. These combined reactions make palm shell a promising biomass feedstock in renewable energy systems.

Percentage of gasification conversion

Gasification conversion (%GC) represents the efficiency of converting solid biomass into gaseous products during the gasification process. It is a crucial parameter to evaluate the performance of a gasifier and the effectiveness of the process. The GC percentage is calculated using Equation 1. The results of the gasification conversion percentage calculation are shown in Figure 1.

Figure 1 illustrates the comparison of %GC (gasification conversion percentage) values at various temperatures (350 °C to 650 °C) between palm shells and coal. The gasification results for palm shells and coal exhibit different patterns across the temperature range. Palm shells achieve the highest gasification conversion value (%GC) of 46.17% at 550 °C, indicating optimal performance at moderate temperature ranges. This is supported by the high volatile matter and lignin content in palm shell biomass, which enhances gas release during the gasification process.

In contrast, coal achieves its highest %GC of 54.76% at a low temperature (350 °C) but experiences a sharp decline at higher temperatures, attributed to the dominance of fixed carbon, which is more challenging to decompose. The decrease in efficiency at higher temperatures (600–650 °C)

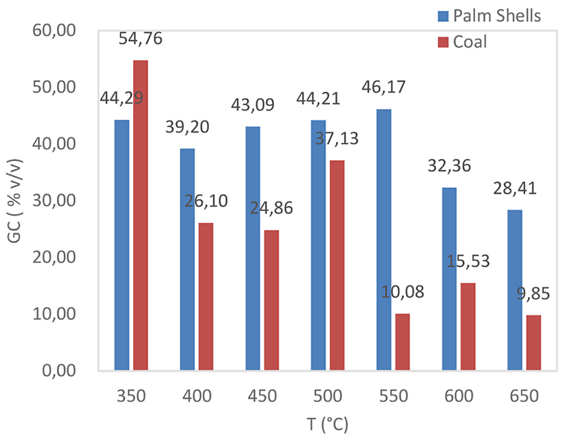

Figure 1. The comparison of %GC at various temperatures between palm shells and coal

for both materials is caused by secondary decomposition, which inhibits gas release.

Recent literature supports these findings, showing that biomass with high lignin content, such as palm shells, demonstrates stable performance in the gasification process at moderate to high temperatures (Barco-Burgos et al., 2021). Meanwhile, coal performs better at lower temperatures due to its stable carbon properties within that range (Sher et al., 2020). Other studies also note that the thermal characteristics of biomass, such as fixed carbon content and volatile matter properties, significantly influence gasification efficiency.

Net gasification conversion (%NGC)

%NGC typically represents the net efficiency of converting the biomass into gaseous products, accounting for the total energy or mass balance during the gasification process. It is often calculated to evaluate the effectiveness of the process, excluding losses or unconverted residues.

The GC percentage is calculated using Equation 2. The results of the net gasification conversion percentage calculation are shown in Figure 2.

Figure 2 shows that NGC increases with rising temperatures for both feedstocks. However, coal consistently produces higher NGC compared to palm kernel shells, especially at temperatures between 400 °C and 650 °C. At 650 °C, the NGC of palm kernel shells reaches 52.87%, approaching that of coal at 58.25%. These results align with research findings that suggest biomass, such as palm kernel shells, tends to produce lower NGC compared to coal at lower temperatures due to its higher fixed carbon content. However, increasing the temperature can improve the gasification performance of biomass. Studies also demonstrate that the use of catalysts, such as Al/Fe-based metal catalysts, can enhance the efficiency of biomass gasification. Although the NGC of palm kernel shells is lower than that of coal, the development of catalytic technology can improve its efficiency, making biomass like palm kernel shells a more environmentally friendly alternative energy source.

The ratio of GC and NGC

The ratio of GC and NGC reflects the comparison between combustible gases and non-combustible gases produced during thermal processes. This ratio is critical for evaluating the combustion efficiency of fuels, such as biomass and coal, in energy generation. GC typically includes gases like H_2, CH_4, and CO, while NGC comprises gases like CO_2 and N_2. A higher ratio indicates a greater potential of the fuel to produce energy via combustible gases.

Figure 3 shows the comparison of the GC/NGC (gas combustible/non-gas combustible**)** ratio between palm shell and coal at various temperatures. At 350 °C, coal exhibits a higher combustible gas dominance (5.09) compared to palm shell (2.03) due to its initial volatile content. However, at medium temperatures (450–500 °C), palm shell dominates with a ratio of 2.56, attributed to the decomposition of hemicellulose, cellulose, and lignin, consistent with the thermal properties of biomass. A decline in the ratio above 550 °C reflects the depletion of combustible material. This indicates that palm shell is more effective at medium to high temperatures compared to coal, which is more stable at lower temperatures. Studies by Tang et al, support this finding, highlighting that

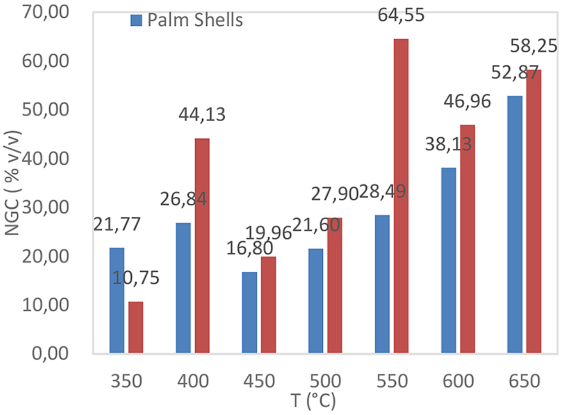

Figure 2. The comparison of NGC at various temperatures between palm shells and coal

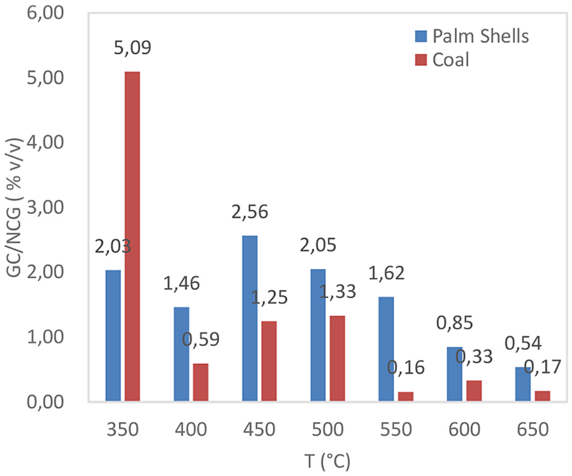

Figure 3. Comparison of GC/NGC ratios for palm shell and coal across various temperatures

biomass's high volatility enhances combustion efficiency compared to coal (Tang et al., 2024)

Heating value

Heating value refers to the amount of energy released during the combustion of a fuel. It is typically divided into two categories: higher heating value (HHV) and lower heating value (LHV). HHV includes the total energy released, accounting for the heat contained in the water vapor produced during combustion, while LHV excludes this energy, assuming the water remains in vapor form and does not condense. HHV is used when calculating the maximum energy output, while LHV gives a more realistic measure of energy available for practical use. The HHV and LHV values are calculated using Equation 3 and 4. The results of the HHV and LHV calculations are shown in Figures 4 and 5.

Figure 4 illustrates the trend of HHV in the gasification of palm kernel shells and coal across a temperature range of 350 °C to 650 °C. At 350 °C, the HHV of coal reaches its highest value (25.38 MJ/Nm³), significantly surpassing that of palm kernel shells (13.64 MJ/Nm³). However, at the optimal temperature of 550 °C, the HHV of palm kernel shells increases to 12.40 MJ/Nm³, exceeding that of coal, which drops to 2.95 MJ/Nm³. The decline in HHV at higher temperatures (600–650 °C) is attributed to secondary decomposition reactions, such as hydrocarbon cracking, which produce lower-energy gases. Recent research by Osei et al, demonstrates that, under specific conditions, the gasification of palm kernel shells can yield a calorific value comparable to coal, positioning it as a more environmentally friendly and sustainable alternative fuel source (Osei et al., 2023). The Figure 5 shows that the LHV (Lower Heating Value) of palm kernel shell

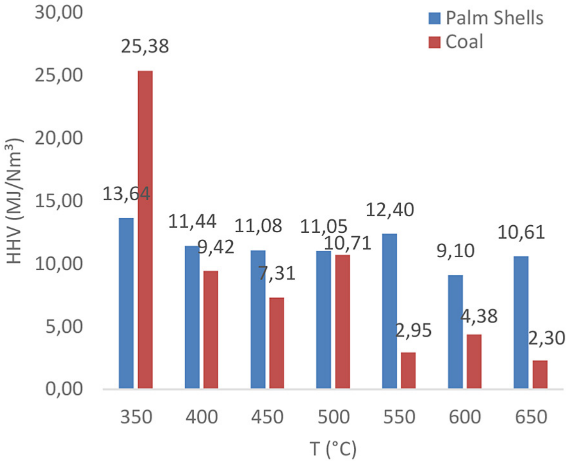

Figure 4. HHV of palm kernel shell gasification vs coal at various temperatures

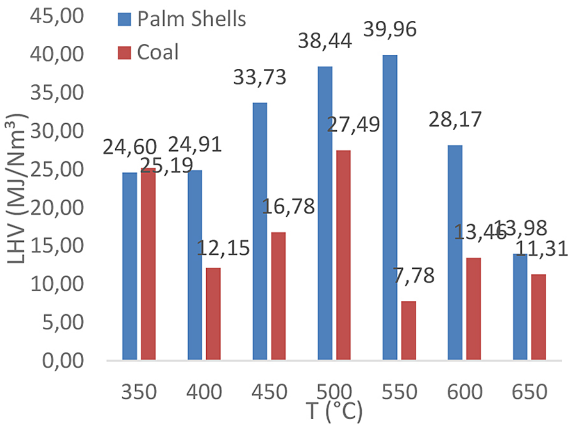

Figure 5. LHV of palm kernel shell gasification vs coal at various temperatures

gasification is higher than that of coal at the optimal temperature range of 500 °C to 550 °C. At 500 °C, the LHV of palm kernel shells reaches 38.44 MJ/Nm³, and at 550 °C, it peaks at 39.96 MJ/Nm³, while coal's LHV significantly drops at these temperatures. The decrease in LHV at higher temperatures (> 600 °C) is due to secondary decomposition reactions, producing gases with lower energy content. Recent studies by Fauzi et al, demonstrate that palm kernel shell gasification produces gases with higher calorific values and is more environmentally friendly compared to coal, making it a more efficient renewable fuel option (Fauzi et al., 2020)

Gasification efficiency

The efficiency of gasification is expressed in two key parameters: %CCE (cold gas conversion efficiency) and %CGE (cold gas efficiency). Both represent different aspects of the gasification process efficiency. %CCE and %CGE are defined in Equations 5 and 6, respectively, with the calculated results presented in Figure 6 and 7.

Figure 6 illustrates the comparison of fixed carbon conversion percentages (%CCE) between palm kernel shells and coal at various temperatures. The results indicate that palm kernel shells exhibit a higher %CCE than coal at all temperatures. At a low temperature (350 °C), palm kernel shells achieve the highest value (89.19%), whereas coal records 78.74%. As the temperature increases, the %CCE for both materials decreases significantly. However, the decline in coal is far more drastic, reaching as low as 7.07% at 650 °C, compared to palm kernel shells, which still record 56.40%. This suggests that palm kernel shells are more reactive than coal, particularly at low to moderate temperatures.

These findings align with research by Nabila et al, which indicates that biomass, including palm kernel shells, has a high lignocellulose content, making it more easily degradable and capable of achieving higher fixed carbon conversion at lower

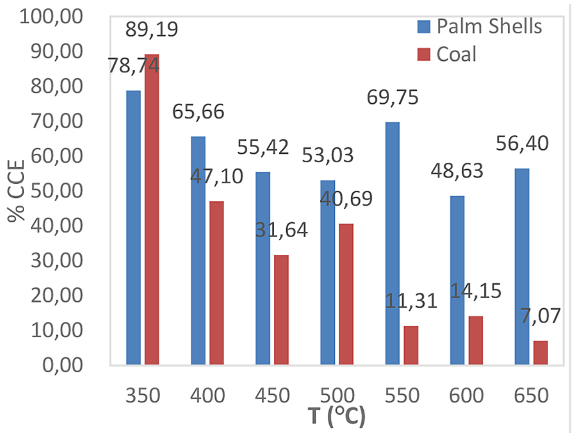

Figure 6. Comparison of fixed carbon conversion percentages between palm kernel shells and coal

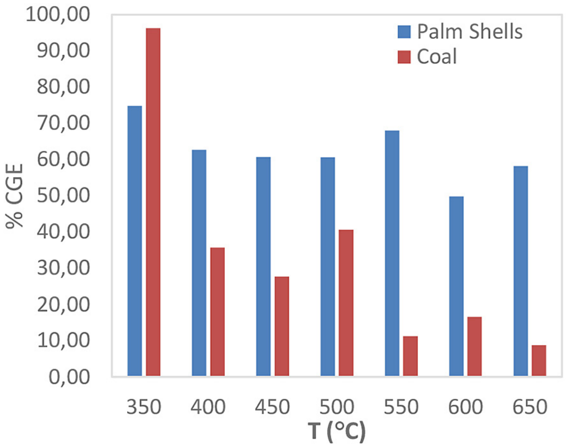

Figure 7. Comparison of cold gas efficiency between palm kernel shells and coal

to moderate temperatures (Nabila et al., 2023). In contrast, coal, with its more complex aromatic carbon structure, requires higher temperatures to undergo significant conversion. The sharp decline in coal's %CCE at high temperatures reflects the depletion of reactive carbon components. Research by Wang & Wu (2023) highlights the advantages of biomass in thermochemical conversion compared to coal, especially in combustion and gasification processes.

Figure 7 shows the comparison of cold gas efficiency (CGE) percentages between palm kernel shells and coal over a temperature range of 350–650 °C. At low temperatures (350 °C), coal exhibits a very high CGE value, reaching approximately 90%, significantly outperforming palm kernel shells, which achieve only around 70%. This indicates that at low temperatures, coal is more efficient in converting carbon into gas compared to palm kernel shells. However, as the temperature increases, the CGE of coal decreases drastically, dropping to nearly 10% at 650 °C. This significant decline reflects the depletion of reactive carbon in coal, leading to reduced conversion efficiency at high temperatures. In contrast, palm kernel shells display a more stable performance. Despite a slight decline, the CGE of palm kernel shells remains at approximately 50% at 650 °C. This suggests that palm kernel shells contain high levels of volatile matter and lignocellulose, making them more reactive over a broader temperature range.

These findings are consistent with recent studies. Kaniapan et al. (2021) reported that biomass such as palm kernel shells is more easily degraded due to its high lignocellulose content, enabling better conversion efficiency at low to moderate temperatures. Conversely, coal, with its complex aromatic carbon structure, requires higher temperatures to achieve significant conversion, as highlighted by Gao et al. (2023) further supported these findings by demonstrating that biomass outperforms coal in producing efficient syngas through gasification at high temperatures. Overall, the graph underscores the superiority of palm kernel shells as a more efficient alternative feedstock for gasification compared to coal, particularly at high temperatures.

Statistical and descriptive analysis

Statistical and descriptive analyses were conducted to evaluate the results across several aspects, including Proximate & Ultimate Analysis, gas composition, gasification efficiency, and HHV and LHV values. Additional data from the literature were utilized to supplement the single-test results and provide broader descriptive trends. A temperature of 500 °C was selected as the focus of the analysis due to its relevance to gasification optimization. According to the literature, this temperature is often considered optimal for light hydrocarbon reforming and volatile decomposition, producing gas with a high H_2 content. Experimental data also showed that, at this temperature, palm kernel shells yielded the maximum H_2 concentration (24.19%), supporting further analysis at this temperature (Table 3).

Proximate & ultimate analysis

The data indicate that palm kernel shells have a higher volatile matter content compared to coal, which supports a more efficient gasification

Table 3. Proximate and ultimate characteristics of palm kernel shells and coal

Parameters	Unit	Palm kernel shell (Mean ± SD)	Coal (Mean ± SD)	Literature sources
Total Moisture (ar)	%	12.71 ± 0.15	23.76 ± 0.20	(Wang et al., 2021)
Volatile Matter (adb)	%	68.31 ± 0.32	41.75 ± 0.28	(Ahmed et al., 2020)
Fixed Carbon (adb)	%	18.29 ± 0.25	42.97 ± 0.30	(Chen et al., 2022)
Gross Calorific Value	kcal/kg	4359 ± 23	6304 ± 31	(Ahmed et al., 2020)

process at medium to high temperatures. Conversely, the higher fixed carbon content in coal results in lower efficiency for certain applications.

The composition of the generated gas

The gas composition analysis results are presented in Table 4, incorporating single-test data along with additional data from international literature to enhance the validity of the analysis.

The trend shows that palm shell generates higher H_2 at 500 °C compared to coal. Conversely, coal has a higher CH_4 content.

Gasification efficiency (%CCE and %CGE)

The results of the gasification efficiency analysis are presented in Table 5, including single test data as well as additional data from international literature to complement the descriptive analysis.

The carbon conversion efficiency (%CCE) of palm shells demonstrates better stability at medium to high temperatures compared to coal. Literature data supports this finding with higher %CCE values for palm shells at 500 °C. In terms of %CGE, palm shells also show better performance with consistently higher values than coal.

Heating value (HHV and LHV)

The HHV and LHV results for palm shells and coal at various temperatures are presented in Table 6. The trend shows that the HHV of palm shells increases significantly at moderate temperatures, surpassing the value of coal. However, the LHV of both feedstocks exhibits a more similar pattern at high temperatures.

Overall, the test results and literature data show consistent trends in the differences in thermochemical characteristics, gas composition, gasification efficiency, as well as HHV and LHV between palm shells and coal. Palm shells demonstrate superior performance at moderate to high temperatures in producing H_2-rich gas, stable carbon efficiency, and high HHV values. Literature data support these initial indications, although no

Table 4. Gas composition from the gasification of palm kernel shells and coal at different temperatures

Temperature (°C)	Gas	Palm kernel shell (Mean ± SD)	Coal (Mean ± SD)	Literature sources
500	H_2 (%)	24.19 ± 0.50	14.99 ± 0.35	(Chen et al., 2022)
500	CO (%)	0.0184 ± 0.005	0.0383 ± 0.007	(Ahmed et al., 2020)
500	CH_4 (%)	19.99 ± 0.65	22.08 ± 0.55	(Ahmed et al., 2020)
500	CO_2 (%)	4.62 ± 0.15	3.84 ± 0.12	(Chen et al., 2022)

Table 5. Gasification efficiency (%CCE and %CGE) of palm kernel shells and coal at different temperatures

Temperature (°C)	Parameter	Palm kernel shell (Mean ± SD)	Coal (Mean ± SD)	Literature sources
500	%CCE	89.19 ± 1.20	78.74 ± 1.00	(Chen et al., 2022)
500	%CGE	50.00 ± 2.00	44.00 ± 2.50	(Ahmed et al., 2020)

Table 6. HHV and LHV values of palm shells and coal at different temperatures

Suhu (°C)	Parameter	Palm kernel shell (Mean ± SD)	Coal (Mean ± SD)	Literature sources
500	HHV (MJ/Nm³)	12.40 ± 0.30	2.95 ± 0.15	(Ahmed et al., 2020)
500	LHV (MJ/Nm³)	39.96 ± 0.50	38.44 ± 0.45	(Chen et al., 2022)

inferential analysis was conducted. Further research with a more comprehensive experimental design remains necessary.

CONCLUSIONS

This study compared the thermochemical properties and gasification performance of palm kernel shells (PKS) and coal as energy sources. PKS has a higher volatile matter content and lower fixed carbon content, making it more readily decomposable during the gasification process. At medium to high temperatures, PKS produces a higher H_2/CO ratio, demonstrating its potential as a cleaner and more environmentally friendly energy source. In contrast, coal exhibits a higher gross calorific value (HHV) at low to medium temperatures, but its efficiency declines significantly at higher temperatures. PKS also demonstrates more stable carbon conversion efficiency (%CCE) compared to coal across various gasification temperatures, further strengthening its potential as an effective renewable energy feedstock. This analysis is supported by international literature data to complement the results of the experiments conducted. These findings provide an initial indication that PKS has advantages over coal in clean energy applications, particularly at medium to high gasification temperatures. Further research with a more comprehensive experimental design is required to validate these results, develop more efficient gasification technologies, and assess the economic and environmental impacts of utilizing PKS.

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