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Thermal and Kinetic Study of Fine Coal And Palm Kernel Shell Gasification Using TGA Analysis

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Abstract

Indonesia is rich in natural resources, including coal and palm kernel shells (PKS), which can be used in the gasification process. This study compares the gasification potential of palm kernel shells and fine coal, focusing on their thermal properties and activation energy. Thermogravimetric Analysis (TGA) shows that PKS have higher volatile matter (67.25%) and lower fixed carbon (20.90%) than fine coal (33.53% volatile matter, 32.98% fixed carbon). at 450 °C, PKS lose 11% of their mass in one hour and reach a 78% loss by the end of the process, while fine coal loses 70% after more than 200 minutes. The activation energy for PKS is lower (38.925 J/mol) than fine coal (41.012 J/mol). In gasification, palm kernel shells produce more hydrogen (26% mol) and less carbon dioxide (11% mol) than fine coal, which produces more methane (28% mol) and carbon dioxide (22% mol). These results suggest that PKS are a more efficient and eco-friendly option for gasification.

Keywords: Fine coal, palm kernel shells, activation energy, thermogravimetric analysis (TGA), gasification

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Abstrak (Indonesian)

Indonesia kaya akan sumber daya alam, termasuk batubara dan cangkang sawit, yang keduanya dapat dimanfaatkan dalam proses gasifikasi. Penelitian ini membandingkan potensi gasifikasi cangkang sawit dan batubara halus, dengan fokus pada karakteristik termal dan energi aktivasi mereka. Analisis Termogravimetri (TGA) menunjukkan bahwa cangkang sawit memiliki kandungan zat volatil yang lebih tinggi (67,25%) dan karbon tetap yang lebih rendah (20,90%) dibandingkan batubara halus (33,53% zat volatil, 32,98% karbon tetap). Pada suhu 450 °C, cangkang sawit kehilangan 11% massa dalam satu jam dan mencapai 78% pada akhir proses, sementara batubara halus kehilangan 70% massa setelah lebih dari 200 menit. Energi aktivasi cangkang sawit lebih rendah (38,925 J/mol) dibandingkan batubara halus (41,012 J/mol). Dalam gasifikasi, cangkang sawit menghasilkan lebih banyak hidrogen (26% mol) dan lebih sedikit karbon dioksida (11% mol) dibandingkan batubara halus, yang menghasilkan lebih banyak metana (28% mol) dan karbon dioksida (22% mol). Hal ini menunjukkan bahwa cangkang sawit lebih efisien dan ramah lingkungan untuk gasifikasi dibandingkan batubara halus.

Kata Kunci: Batubara, cangkang sawit, energi aktivasi, analisa termogravimetri, gasifikasi

INTRODUCTION

Indonesia is one of the countries rich in natural resources, including coal and palm kernel shells [1]. Coal, as one of the widely used fossils fuels, plays a significant role in energy supply in Indonesia [2]. On the other hand, palm kernel shells, a by-product of the palm oil industry, have great potential to be utilized as an alternative energy source [3]. The use of these two materials in the gasification process can be a solution to increase energy efficiency and reduce dependence on conventional fossil fuels [4].

Gasification is a technology capable of converting solid fuels into gas that can be used for power generation [5]. This process requires a deep understanding of the thermal characteristics and activation energy of the fuels used [6]. Therefore, research on the thermal characteristics and activation energy of coal and palm kernel shells is crucial to enhance the efficiency of the gasification process.

Thermogravimetric Analysis (TGA) is a thermal analysis technique used to measure the mass change of a material as a function of temperature or time in a specific atmosphere, such as air or nitrogen. This method is widely employed to determine key parameters such as mass loss due to thermal decomposition, volatilization, and combustion. In the context of gasification, TGA plays a crucial role in understanding the thermal degradation characteristics of solid fuels, including coal and biomass such as Palm Kernel Shell (PKS). Several previous studies have utilized TGA to analyze these fuels. For instance, a study by Wei *et al.* [7] demonstrated that TGA can be used to understand the synergistic effects in the co-gasification of coal and biomass. Hussain *et al.* [8] analyzed the thermal decomposition characteristics of PKS using TGA and found that its high volatility enhances gasification efficiency. Additionally, Hameed *et al.* [9] compared the thermal decomposition of coal and PKS using a combination of TGA and FTIR, providing insights into the differences in thermal characteristics and reaction mechanisms of these fuels. By incorporating this explanation into the introduction, readers are expected to gain a more comprehensive understanding of the working principles of TGA and how this method is utilized in relevant studies.

Coal and palm kernel shells have great potential as fuels in the gasification process, but several challenges must be addressed [10]. One of them is the difference in thermal characteristics between these two materials, which can affect the efficiency of the gasification process. In addition, information regarding the activation energy of these two materials in the context of gasification is still limited. Therefore, this study focuses on analyzing the thermal characteristics and activation energy of coal and palm kernel shells to better understand their potential as fuels in gasification.

From an environmental perspective, PKS gasification produces lower carbon dioxide emissions compared to coal, thereby helping to reduce the carbon footprint. Biomass, such as PKS, is also considered carbon-neutral because the carbon dioxide released during combustion was previously absorbed by plants during their growth. Additionally, coal generally contains a higher sulfur content than biomass, which can potentially lead to SO_2 emissions and acid rain. Studies have shown that biomass, including PKS, tends to have lower ash content than coal, resulting in less combustion residue and reducing environmental pollution [11,12].

From an economic perspective, PKS is a byproduct of the palm oil industry that is abundantly available in Indonesia, making it a more affordable and sustainable fuel. Moreover, increasingly stringent environmental regulations on coal usage have led to rising costs, while PKS offers a more economical alternative. The utilization of PKS is also aligned with Indonesia's renewable energy policies, which promote biomass utilization and may provide incentives or subsidies from the government. By adding this explanation to the Introduction section, we aim to clarify the key reasons why PKS is a better alternative to coal, both environmentally and economically.

Various studies have made significant contributions to understanding and optimizing the use of coal and palm kernel shells as fuels in gasification. Wei *et al.* [13] investigated the co-gasification of coal and biomass, including palm kernel shells, to understand the synergistic effects and kinetics that can improve process efficiency. Hussain *et al.* [8] conducted thermogravimetric analysis and kinetics on palm kernel shells, providing important data on thermal characteristics and activation energy. Ahmad *et al.* [14] examined the gasification performance of coal and palm kernel shell mixtures, showing an increase in gas production and overall efficiency. Zhang *et al.* [15] developed an advanced kinetic model to predict the gasification behavior of palm kernel shells, focusing on improving efficiency and reducing emissions. Finally, Teh *et al.* [16] conducted a comparative study on the thermal decomposition and gasification of coal and palm kernel shells using TGA and FTIR, providing new insights into the differences in thermal characteristics and reaction mechanisms in the context of gasification. These studies reinforce the understanding of the potential and challenges in using coal and palm kernel shells as fuels in gasification while paving the way for further innovations in energy technology.

Although there have been studies examining the thermal characteristics of coal and palm kernel shells separately, research specifically comparing them in the context of gasification is still rare. Moreover, studies on the activation energy of palm kernel shells in gasification are still scarce. This gap highlights the need for further research to understand how the thermal characteristics and activation energy of these two materials can be integrated to improve gasification efficiency.

This research contributes to the development of knowledge on gasification with a focus on comparing the thermal characteristics and activation energy between coal and palm kernel shells. The novelty of this research lies in the in-depth comparative analysis of these two materials, which is expected to provide new insights into optimizing the gasification process. The main objective of this study is to examine and compare the thermal characteristics and activation energy of coal and palm kernel shells as fuels in the gasification process. Thus, this study is expected to contribute to the development of more efficient and sustainable gasification technology.

MATERIALS AND METHODS

Materials

This study utilized two primary materials: coal and palm kernel shell. The coal samples were obtained from PTBA Kertapati, South Sumatra, Indonesia, selected for its representative characteristics for gasification in Indonesia. The palm kernel shell used in this research was sourced from the CPO industry at the Dermaga Pelabuhan Dalam, Tanjung Api-Api, Banyuasin Regency, South Sumatra. The selection of palm kernel shell was based on its abundant availability and potential as an alternative fuel.

Methods

The first stage of the research involved the preparation of coal and palm kernel shell samples. Both materials were dried at a temperature of 100-105 °C until a constant moisture level was achieved, aiming to remove water content that could affect the analysis results. After drying, the materials were ground to achieve a uniform particle size of approximately 100 mesh.

Thermal characteristics analysis was conducted using a Thermogravimetric Analyzer (TGA). In this analysis, the coal and palm kernel shell samples were heated from room temperature to 1000 °C. The purpose of the TGA analysis was to determine the melting point, decomposition temperature, and residue remaining after combustion, which are critical parameters in the gasification process.

The activation energy of both materials was calculated using data obtained from the TGA. The method employed was the Arrhenius method, based on the decomposition rate of the samples at various temperatures. TGA data was processed to create graphs of time versus weight loss, time versus temperature rise, and activation energy.

The gasification process was applied using a fixed-bed gasification reactor. In this stage, the coal and palm kernel shell samples were gasified at temperatures around 600 °C with controlled airflow or oxygen supply. The gases produced from the gasification process, such as CO, H_2, CH_4, and CO_2, were measured using a gas chromatograph (GC) to determine gasification efficiency and the composition of the produced gas.

The data obtained from the thermal analysis and activation energy were then compared to identify the differences and advantages of each material in the gasification process. The results of this research are expected to provide a comprehensive understanding of the potential of coal and palm kernel shell as fuels in the gasification process

Analysis data

The results from TGA, illustrating the variation in sample mass during heating, reveal the material's decomposition characteristics across different temperature ranges. The processed data help identify the peak decomposition temperature, the extent of mass loss, and the temperature where notable decomposition takes place. This analysis provides insights into the thermal stability and decomposition efficiency of each material.

To determine the activation energy, the Arrhenius equation was employed to describe the relationship between temperature and reaction rate. The Arrhenius equation is expressed as:

$$k=Ae^{-\frac{Ea}{RT}} \quad (1)$$

The activation energy (Ea) was calculated using TGA data by plotting ln(k) against 1/T. The Ea value was derived from the slope of this plot using the formula:

$$Ea= -Slope \times R \quad (2)$$

The slope of the plot was obtained by performing a linear regression analysis on the ln(k) data plotted against 1/T. Identify the components of the syngas generated through the Gas Chromatography (GC) method. Subsequently, determine the process efficiency, heating value, and overall efficiency of the gasification process. The percentage of gasification

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completion (%GC) can be calculated using the formula:

$$\%GC = \left(\frac{W_{initial}\text{-}W_{Residual}}{W_{initial}}\right) \text{ x } 100 \qquad (3)$$

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

The general formula for determining the percentage of non-gasified components (%NGC) is given by:

$$\%NGC=100\text{-}\%GC \qquad (4)$$

RESULTS AND DISCUSSION

Proximate analysis of coal waste and palm kernel shell

Proximate analysis is a fundamental method used to determine the chemical composition of solid fuels such as coal and biomass [17]. This analysis involves measuring several key parameters, including moisture content, volatile matter, ash content, and fixed carbon. The data obtained from proximate analysis provide insights into the fuel's quality, its efficiency in energy conversion processes, and the potential residue left after combustion.

Figure 1 and **Table** 1 present the results of the proximate analysis of two fuels, fine coal and palm kernel shell. Proximate analysis is a common chemical analysis used to determine the fuel composition, including moisture content, volatile matter, ash content, and fixed carbon [18].

The proximate analysis results for fine coal and palm kernel shell have significant implications for the gasification process, which is a method of converting solid fuel into gas that can be used as an energy source. The higher moisture content in fine coal (30.31%) compared to palm kernel shell (10.72%) indicates that more energy will be required to evaporate the water in fine coal during gasification, which may reduce the efficiency of the process. On the other hand, palm kernel shell has a much higher volatile matter content (67.25%) compared to fine coal (33.53%), meaning that palm kernel shell will decompose more easily and quickly into gas during gasification. The ash content of both materials is relatively low, with palm kernel shell having a lower ash content (1.24%) compared to fine coal (3.18%), meaning that palm kernel shell will leave behind less solid residue, which is advantageous in the gasification process.

Furthermore, fine coal has a higher fixed carbon content (32.98%) compared to palm kernel shell (20.90%). This fixed carbon requires more energy and time to break down during gasification, but it also contributes to greater gas production. Dry basis analysis shows that palm kernel shell has higher volatility (84.41%) compared to fine coal (52.99%), indicating greater efficiency in generating combustible gas. However, the lower fixed carbon content in palm kernel shell suggests that fine coal may be superior in terms of total gas production during gasification. Recent studies by Dechapanya *et al.* [12] indicates that palm kernel shell has a higher volatile matter content (67.25%) and lower ash content (1.24%) compared to fine coal, suggesting that palm kernel shell may be more efficient in the gasification process.

Overall, palm kernel shell is better suited for gasification processes that require rapid decomposition with minimal ash residue [19], while fine coal is more appropriate for stable and higher energy production in the long term [20]. The selection of fuel for gasification should consider these characteristics to achieve the desired goals in the energy conversion process.

Thermogravimetric analysis (TGA)

The effect of temperature on the gasification process

Gasification is a thermochemical process that converts solid fuels, such as fine coal and biomass (palm shell), into gas that can be used as an energy source [21]. This process occurs at high temperatures, where temperature plays a crucial role in determining the rate and efficiency of the reactions involved [22].

The data presented in **Figure** 2 depict the temperature changes in Fine Coal and Palm Shell during the heating process in gasification. In the initial stage, the temperature gradually increases, indicating the drying phase. The temperature then rises sharply, reaching around 950 °C for Fine Coal and 900 °C for Palm Shell, marking the entry of the materials into the pyrolysis and oxidation zones, where the fuel begins to decompose into gas and char. After reaching the peak, the temperature decreases, indicating the reduction phase, where char is converted into gas. Gasification requires high temperatures, typically above 700 °C, to convert solid fuel into energy-rich gas. The difference in temperature patterns between Fine Coal and Palm Shell suggests that the type of fuel affects the gasification process.

Table 1. Proximate Analysis Results of Fine Coal and Palm Shell

Sample	Parameters (%)						
	Moisture	Volatile Matter	Ash Content	Fixed Carbon	Volatile Matter (Dry Basis)	Ash Content (Dry Basis)	Fixed Carbon (Dry Basis)
Fine Coal 1	30.32	33.45	3.16	33.08	52.85	2.44	44.71
Fine Coal 2	30.32	33.47	3.22	32.99	52.90	2.57	44.53
Fine Coal 3	30.28	33.68	3.16	32.87	53.21	2.44	44.35
Average Fine Coal	30.31	33.53	3.18	32.98	52.99	2.48	44.53
Palm Shell 1	10.77	67.16	1.26	20.81	84.34	-2.19	17.85
Palm Shell 2	10.81	67.44	1.21	20.54	84.75	-2.27	17.52
Palm Shell 3	10.57	67.15	1.25	21.35	84.13	-2.22	18.07
Average Palm Shell	10.71	67.25	1.24	20.90	84.40	-2.22	17.81

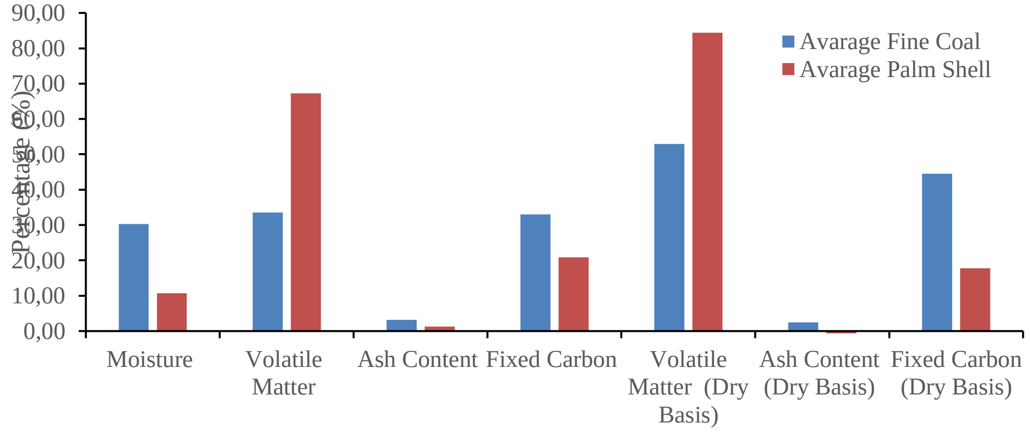

Figure 1. Proximate Analysis Results of Fine Coal and Palm Shell

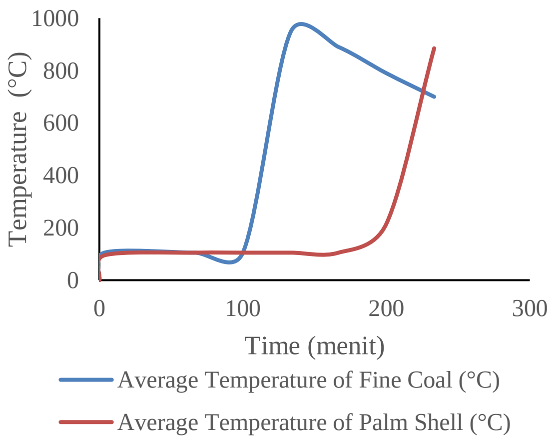

Figure 2. Relationship Between Temperature and Time

Fine Coal tends to maintain a higher temperature for a longer duration, which may produce more char [23], while Palm Shell, which experiences a temperature increase again, may indicate potential for re-combustion or different ongoing reactions. research by Adnan et al, analyzed the combustion performance of syngas produced from palm kernel shell in a gas burner. The study observed that the wall temperature profiles for burnt syngas produced via downdraft gasification were higher with a longer duration under fuel-rich conditions, indicating that the type of fuel influences the temperature distribution during combustion [24].

Percentage of weight loss over time

The percentage of mass loss in fine coal and palm shell provides important insights into the decomposition rate and thermal reactivity of these raw materials during the heating process [25]. **Figure** 3 presented show the relationship between heating time and the percentage of mass loss in fine coal and palm shell. This data offers an overview of the decomposition rate of these raw materials in the context of the gasification process. The percentage of mass loss in fine coal and palm shell is a key indicator reflecting the decomposition rate and thermal reactivity of both materials during the heating process.

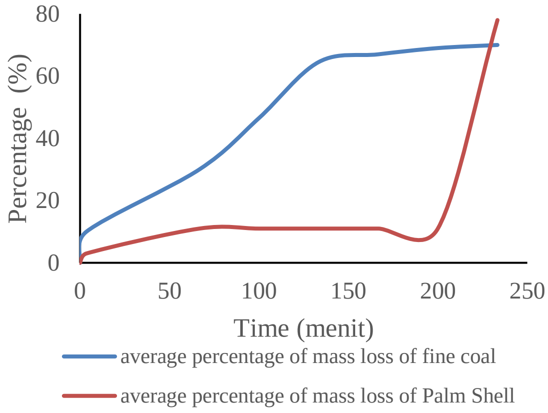

Figure 3. Relationship Between Percentage of mass loss and Time.

The analysis data shows that fine coal and palm shell experience mass loss when heated over a certain period. Fine coal begins to lose mass significantly from the start of heating, with the percentage continuously increasing to 70% after more than 200 minutes. In contrast, palm shell shows a slower and more stable mass loss, with only 11% of the mass lost after about an hour of heating, gradually increasing to 78% by the end of the process.

These differences in mass loss rates reflect how the two materials react to heat. Fine coal, which decomposes more quickly, tends to release volatile gases faster, making it an efficient material for rapid gasification. On the other hand, palm shell, with its slower reactivity, provides a more stable and sustained gas release, which can support the continuity of the gasification process.

Studies have shown that the thermal degradation and gasification behavior of both biomass and coal play a crucial role in optimizing the gasification process. For instance, a study "Thermal Degradation and Gasification of Biomass and Coal Blends for Syngas Production" by Liu *et al.* [25], discusses how biomass materials like palm shell and coal interact during gasification, emphasizing their mass loss differences. This synergy allows for a more optimal gasification process in producing synthesis gas, which is crucial for sustainable energy applications. Fine coal can accelerate the initial reaction, while palm shell can extend the reaction and ensure that gasification continues efficiently over a longer period.

In gasification processes, the combination of these two materials can offer significant advantages. Fine coal can accelerate the initial reaction, while palm shell can extend the reaction and ensure that gasification continues efficiently over a longer period [26]. This synergy allows for a more optimal gasification process in producing synthesis gas, which is crucial for sustainable energy applications. For instance, a study by Dechapanya *et al.* [12] utilized PKS in an air gasification process to produce syngas, employing biochar from agricultural residues to enhance tar removal. The results demonstrated that the addition of biochar significantly increased tar capture, improving the quality of the produced syngas. This highlights the potential of PKS as an efficient and environmentally friendly renewable energy feedstock when combined with appropriate additives [27].

Activation energy using the Kissinger method

The Kissinger method is a technique used to determine the activation energy in thermochemical processes through the analysis of thermal data [28]. Activation energy is a measure of the energy required to initiate a chemical reaction or physical process [29]. **Table** 3 and **Figure** 4 present the temperature, time, and heating rate measurements for two types of samples: Fine Coal and Palm Shell.

Figure 4 shows the activation of two different materials, Palm Shell and Fine Coal, which were analyzed using thermal methods. The x-axis represents the value of 1/T in Kelvin, while the y-axis shows the value of β/T^2, where β is the heating rate. From the graph, the slope of the trendlines is obtained. The slope for Palm Shell is -4682.5, and for Fine Coal, it is -4931.5. Based on these slopes, the activation energy of Fine Coal and Palm Shell can be calculated using the Kissinger equation: Slope = $\frac{-E_a}{R}$, where Ea is the activation energy and R is the ideal gas constant (R ≈ 8.314 J/mol·K). Therefore, Ea = -Slope x R.

From the graph, the activation energy is calculated to be 38.925 J/mol for Palm Shell and 41.012 J/mol for Fine Coal. This indicates that Fine Coal requires more energy to initiate the reaction compared to Palm Shell. In other words, Fine Coal has a higher activation energy, meaning that more thermal energy is needed to break down the coal into volatile components and gases that can be used as fuel. Meanwhile, with slightly lower activation energy, Palm Shell tends to react more easily and quickly under gasification conditions compared to Fine Coal. This means that biomass gasification, such as with Palm Shell, can be carried out at lower temperatures or with less initial energy input, ultimately saving energy and reducing operational cost [30].

Table 3. Data 1 /T and ln(β/T²) for Activation Energy Analysis of Fine Coal and Palm Shell

T (°C)	Fine Coal					Palm Shell				
	t (min)	β (°C/min)	T (K)	1/T	ln (β/T²)	t (min)	β (°C/min)	T (K)	1/T	ln (β/T²)
32	0	-	305.15	0.00310	-	0	-	305.15	0.00310	-
50	7.1	2.54	323.15	0.00309	-10.63	9.71	1.85	323.15	0.00310	-10.94
100	12.33	9.56	373.15	0.00268	-9.59	14.98	9.49	373.15	0.00268	-9.59
150	15.58	15.38	423.15	0.00236	-9.36	21.63	7.52	423.15	0.00236	-10.08
200	24.50	5.61	473.15	0.00211	-10.60	24.98	14.93	473.15	0.00211	-9.62
250	32.33	6.39	523.15	0.00191	-10.67	28.23	15.38	523.15	0.00191	-9.79
300	40.43	6.17	573.15	0.00174	-10.88	30.72	20.08	573.15	0.00175	-9.70
350	46.5	8.24	623.15	0.00160	-10.76	32.83	23.70	623.15	0.00161	-9.70
400	56.08	5.22	673.15	0.00149	-11.37	34.98	23.26	673.15	0.00149	-9.88
450	62.42	7.89	723.15	0.00138	-11.10	36.75	28.25	723.15	0.00138	-9.83
500	68.73	7.92	773.15	0.00129	-11.23	38.55	27.78	773.15	0.00129	-9.98

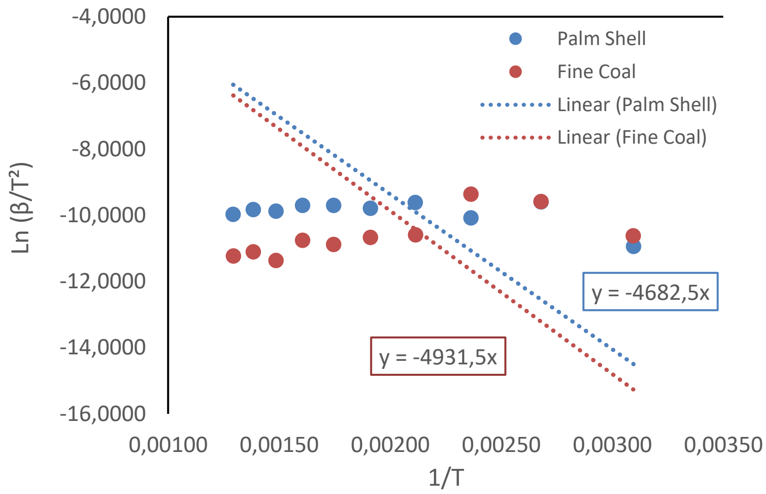

Figure 4. Kissinger Plot Determine Activation Energy

For instance, a study by Umar *et al.* [30] investigated the thermal degradation kinetics of PKS and low-grade Indian coal (LC) at various heating rates. The research found that the activation energy for PKS was 56.92 kJ/mol, while for LC, it was 74.69 kJ/mol. This indicates that PKS requires less energy to initiate the gasification process compared to fine coal, highlighting its potential as an efficient and environmentally friendly renewable energy feedstock.

Gasification process of fine coal and palm shells

Table 4 show the comparison of gas composition produced from Fine Coal and Palm Shell at a temperature of 450 °C. This data provides an overview of the potential value of these two materials as sources of syngas, a synthetic gas that typically consists of a mixture of carbon monoxide (CO) and hydrogen (H_2). Syngas plays a crucial role in various industrial processes, including the production of liquid fuels, methanol, and other chemicals [31].

Based on **Figure** 5, it is evident that both Fine Coal and Palm Shell produce the same molar percentage of CO, at 18%. However, there is a significant difference in the composition of H_2, with Palm Shell generating 26% mol H_2, which is much higher compared to Fine Coal, which only produces 16% mol H_2. Additionally, Fine Coal produces more methane (CH_4) and carbon dioxide (CO_2), with percentages of 28% and 22% respectively, compared to Palm Shell, which only produces 19% CH4 and 11% CO_2.

In syngas, a high content of CO and H_2 is highly desirable, as these two components are the primary raw materials in various industrial chemical processes. In this regard, Palm Shell appears to be superior as a syngas feedstock, given its higher H_2 content and lower CH_4 and CO_2 content. The lower CH_4 content is advantageous because CH_4 is less reactive in syngas processes, while CO_2 is often considered an undesirable byproduct that can reduce process efficiency.

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Overall, this analysis indicates that Palm Shell is a better feedstock than Fine Coal for syngas production at 450 °C. The gas composition produced by Palm Shell, with its higher ratio of CO and H_2, makes it a more suitable choice for industrial applications requiring high-quality syngas. For instance, a study by Andican *et al.* [32] investigated the catalytic gasification of fine coal using natural zeolite as a catalyst. The research found that the addition of zeolite increased the CO content in the syngas, achieving a hydrogen-to-carbon monoxide (H_2/CO) ratio greater than 1, which is desirable for various industrial applications. This indicates that fine coal, when combined with appropriate catalysts, can produce syngas with a composition suitable for industrial use.

Table 4. Gas Composition of Fine Coal and Palm Shell at 450 °C

Parameters	Fine Coal	Palm Shell
CO (% Mol)	18	18
H_2 (% Mol)	16	26
CH_4 (% Mol)	28	19
CO_2 (% Mol)	22	11

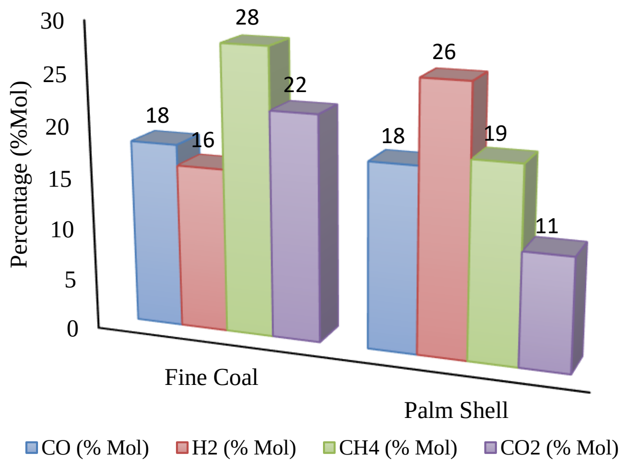

Figure 5. Gas composition percentages of fine coal and palm shell.

CONCLUSION

Based on the research results, palm kernel shells have more favorable characteristics for gasification compared to fine coal, due to their higher volatile matter content and lower fixed carbon. Additionally, palm kernel shells show faster mass loss at gasification temperatures and have lower activation energy, indicating a more efficient process. The gasification results, which produce higher hydrogen and lower carbon dioxide, further confirm the potential of palm kernel shells as a more efficient and environmentally friendly alternative energy source compared to fine coal.

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