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Thermogravimetric Analysis of EFB and Palm Shells as Gasification Fuels: Kinetic and Activation Energy Study

Ria Komala[1,2], Dedi Rohendi[3], Fakhili Gulo[1], Muhammad Faizal[4*]

[1] Environmental Science Doctoral Study Program, Graduate School, Universitas Sriwijaya, Jl. Padang Selasa, No. 524, Bukit Besar, Palembang 30139, Sumatera Selatan, Indonesia
[2] Department of Chemical Engineering, Faculty of Engineering, Universitas Tamansiswa, Jl. Tamansiswa No. 261 20 Ilir D. I, Ilir Tim. I, Kota Palembang, Sumatera Selatan, Indonesia
[3] Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Jl.Raya Palembang-Prabumulih Km 32 Indralaya, Ogan Ilir, Sumatera Selatan 30662, Indonesia
[4] Department of Chemical Engineering, Faculty of Engineering, Universitas Sriwijaya, Jl. Raya Palembang Prabumulih Km 32 Indralaya, Ogan Ilir, Sumatera Selatan 30662, Indonesia

[*]*Corresponding Author: muhammadfaizal@unsri.ac.id*

Abstract

Solid waste from palm oil industry such as EFB and palm kernel shells pose environmental challenges if not properly managed. This study investigated the thermal characteristics and decomposition kinetics of EFB and palm kernel shells through proximate analysis and thermogravimetric analysis (TGA). The results indicate that palm kernel shells have a greater fixed carbon content (21.03–21.35%) than does EFB (19.60–20.06%), whereas EFB has a greater ash content (4.74–5.38%) than does palm kernel shells (1.25–1.31%). EFB showed a weight loss of 94.67% after 233.33 minutes of heating, whereas it was 99% for the palm kernel shells. The peak temperatures reached were 936.67 °C for the EFB and 930 °C for the palm kernel shells. At 600°C, EFB produced more syngas than palm kernel shells did. The calculated activation energies were 4482.19 J/mol for EFB and 4484.97 J/mol for palm kernel shells. This research enhances the understanding of the gasification efficiency of these materials, aiding in the optimization of eco-friendly energy production.

Keywords: Empty fruit bunches, palm kernel shells, activation energy, thermogravimetric analysis, gasification

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Abstrak (Indonesian)

Limbah TKKS dan cangkang sawit dapat menimbulkan tantangan lingkungan jika tidak dikelola dengan baik. Penelitian ini mengkaji karakteristik termal dan kinetika dekomposisi dari TKKS dan cangkang sawit melalui analisis proksimat dan analisis termogravimetri (TGA). Hasil penelitian menunjukkan bahwa cangkang sawit memiliki kandungan karbon tetap yang lebih tinggi (21,03–21,35%) dibandingkan dengan TKKS (19,60–20,06%), sedangkan TKKS memiliki kandungan abu yang lebih tinggi (4,74–5,38%) dibandingkan dengan cangkang sawit (1,25–1,31%). TKKS mengalami kehilangan massa sebesar 94,67% setelah pemanasan selama 233,33 menit, sementara cangkang sawit mencapai 99%. Suhu puncak yang tercapai adalah 936,67 °C untuk TKKS dan 930 °C untuk cangkang sawit. Pada suhu 600 °C, TKKS menghasilkan lebih banyak syngas dibandingkan dengan cangkang sawit. Energi aktivasi yang dihitung adalah 4482,19 J/mol untuk TKKS dan 4484,97 J/mol untuk cangkang sawit. Penelitian ini meningkatkan pemahaman tentang efisiensi gasifikasi kedua bahan ini, yang dapat membantu dalam mengoptimalkan produksi energi ramah lingkungan.

Kata Kunci: Tandan Kosong Kelapa Sawit, Cangkang Sawit, Energi Aktivasi, Analisis termogravimetri, Gasifikasi

INTRODUCTION

The palm oil industry is a rapidly growing sector in Indonesia, positioning the country as the largest global producer and exporter[1]. While contributing significantly to the economy through foreign exchange and employment [2], the industry generates considerable waste, particularly solid waste like empty fruit bunches (EFBs) and palm kernel shells [3]. If unmanaged, these wastes can cause environmental issues, including soil and water pollution as well as greenhouse gas emissions [4]. To mitigate these impacts, various waste treatment methods have been developed. EFBs are often repurposed as compost or mulch [5] , while palm kernel shells are commonly used as boiler fuel [6]. Additionally, research has focused on converting these wastes into bio-oil and biochar through pyrolysis, although challenges in efficiency and scalability remain [7]

Gasification presents a promising alternative, converting solid biomass into syngas—a mixture of hydrogen, carbon monoxide, and methane—that can be utilized for energy production or as a chemical industry feedstock [8]. To enhance the efficiency of this process, it is critical to understand the thermal and kinetic decomposition characteristics of EFBs and palm kernel shells,

The gasification process is influenced by the thermal reaction kinetics of the biomass. Reaction kinetics describe the rate and mechanism of biomass decomposition into gas during heating [9]. Understanding these kinetics is crucial for optimizing the operational conditions of gasification, such as temperature and heating rate, to ensure that the process operates efficiently and economically [10]. This is where the role of thermogravimetric analysis (TGA) becomes critical. TGA allows researchers to identify decomposition temperatures and mass loss rates and determine the activation energy of the thermal decomposition process [11].

The activation energy is a key parameter that indicates how difficult it is for a material to decompose [12]. Materials with lower activation energies decompose more easily, making them more efficient in the gasification process [13]. By understanding the thermal characteristics and activation energy of EFB and palm kernel shells, we can determine which is more efficient as a fuel in the gasification process, as well as how to design optimal gasification operating conditions.

Various studies have been conducted to evaluate the potential of biomass as a fuel in the gasification process. Studies by Kittivech and Fukuda [14] indicate that EFB has high energy potential with decomposition characteristics suitable for gasification. Another study by Patrick *et al.* [15] examined the thermal decomposition kinetics of palm kernel shells via thermogravimetry and reported that this material has good thermal stability. However, most previous studies tended to focus on general thermal analysis without delving into the kinetics and activation energy of EFB and palm kernel shells, especially in the context of gasification. Previous studies provide a strong foundation but have not comprehensively compared the thermal characteristics and decomposition kinetics between EFB and palm kernel shells in the context of gasification. This study aims to provide a deeper understanding of the thermal behavior of EFB and palm kernel shells through thermogravimetric analysis.

MATERIALS AND METHODS

Materials

This study uses two main materials, empty palm fruit bunches and palm kernel shells, both of which are solid waste generated by the palm oil industry. These materials were obtained from the CPO industry at Tanjung Api-Api, Banyuasin Regency, South Sumatra. The selection of these materials is based on their high availability and potential as alternative fuel sources.

Methods

Sample preparation

In the initial phase of the research, samples of EFB and palm kernel shells were prepared through several stages. The collected materials were thoroughly washed with distilled water to remove impurities. Subsequently, the samples were dried in an oven at 80°C for 3.5 hours until they reached minimal moisture content. Once the drying process was completed, the samples were ready to undergo further analysis using two main methods, namely proximate analysis and thermogravimetric analysis (TGA).

Proximate analysis

Proximate analysis aims to determine the basic chemical composition of EFB and palm shells, including moisture content, volatile matter, ash, and fixed carbon. This method follows ASTM standards, specifically ASTM D7582, which outlines the procedures for determining these properties. The analysis process involves several steps: first, the sample is heated to a specific temperature to remove moisture, and the reduction in mass is measured to determine the moisture content. The sample is subsequently heated to evaporate volatile components, which are measured as volatile matter. After the volatile matter has been removed, the sample is heated to a higher temperature to burn the organic material, leaving only ash, which represents the ash content. Fixed carbon is calculated as the remaining material that neither evaporates nor burns

Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) was conducted to study the thermal stability and decomposition behavior of EFB and palm kernel shells during heating. This test used the LECO CHN628 TGA, which measures changes in the sample mass as the temperature increases. The sample was gradually heated from room temperature to 1000°C. During the heating process, TGA was used to record the mass loss of the sample at different temperatures, providing insights into the thermal decomposition of the material.

Kinetic and thermodynamic analysis

The data obtained from TGA were used to determine the decomposition kinetics of EFB and palm kernel shells, specifically the rate at which these materials decompose when heated. Additionally, the activation energy was calculated from the TGA data to understand how difficult it is for the material to undergo decomposition. A lower activation energy indicates that the material decomposes more easily, making it more efficient as a fuel in the gasification process

Gasification process

Gasification is carried out using a fixed-bed updraft gasifier or other types of gasifiers. In this process, 5 kg each of EFB and palm shell are fed into the gasification chamber and heated to 600°C with a limited flow of air or a mixture of air and oxygen. The gasification process lasts for 90 minutes, during which the materials undergo pyrolysis, producing volatile gases, tar, and solid char.

After 90 minutes, gas samples are taken for analysis using Gas Chromatography (GC). At high temperatures, EFB begins to undergo pyrolysis, breaking down organic material into volatile gases, tar, and solid products in the form of char (carbon residue). This process occurs without sufficient direct oxygen for complete combustion

Analysis data

Processing TGA data

The data obtained from TGA, which represents the change in the sample mass during heating, shows the decomposition behavior of the material at different temperatures. These data are processed to determine the peak decomposition temperature, mass loss, and the temperature at which significant decomposition occurs. This information is used to assess the thermal stability and ease of decomposition of each material.

Activation energy calculation

To calculate the activation energy, the Arrhenius equation was used to describe the relationship between temperature and reaction rate. The Arrhenius equation is as follows:

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

where k is the rate constant, A is the frequency factor, Ea is the activation energy, R is the universal gas constant (8.314 J·mol^{-1}·K^{-1}), and T is the temperature in Kelvin (K).

To obtain the activation energy (Ea), TGA data was used to plot ln(k) against 1/T, where Ea was calculated from the slope of this plot, using the following formula:

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

The slope of the plot was obtained by performing a linear analysis of the ln(k) data plotted against 1/T.

Interpretation of results

The calculated activation energy and TGA data were interpreted to determine which material is more efficient for use in the gasification process. EFB and palm kernel shells were compared based on their decomposition temperature, mass loss, and activation energy to assess the potential of each material as an environmentally friendly alternative fuel source

The gas composition analysis

In this study, the analysis of gas composition was performed using Gas Chromatography (GC) to identify the primary components of the syngas produced, including hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and carbon dioxide (CO_2). Following the gas composition analysis, the efficiency of the gasification process was evaluated using several key parameters. The Gas Conversion Efficiency (GCE) is used to measure the effectiveness of converting biomass into gas, and it is calculated using the following formula:

$$\%GC = \left(\frac{\text{Gas Volume}}{\text{Biomass Volume}}\right) \text{ x } 100 \quad (3)$$

The higher the %GC, the more efficient the conversion of biomass into syngas. The %NGC (Non-Gas Conversion Efficiency) indicates the portion of biomass that is not converted into gas, and it is calculated using the following formula:

$$\%NGC = 100 - \%GC \quad (4)$$

RESULTS AND DISCUSSION

Proximate analysis of EFB and palm shell

Proximate analysis determines the basic composition of a material, including moisture content, volatile matter, ash, and fixed carbon. This method provides insights into the characteristics of EFB and palm shells, highlighting their potential as gasification feedstocks [16]. The results from six samples, namely, EFB 1, EFB 2, EFB 3, palm kernel shell 1, palm kernel shell 2, and palm kernel shell 3, were analyzed via the ASTM D7582 method, which is a standard method for biomass material analysis. The analysis results are shown in **Table** 1.

Table 1 present the results of a proximate analysis of EFB and palm shell, covering parameters such as moisture, volatile matter, ash content, and fixed carbon. These data are presented both in the as-received state and on a dry basis to provide a comprehensive understanding of the composition of each biomass. This analysis is crucial for understanding the characteristics of these raw materials in the context of their utilization as biomass energy sources.

Table 1. Results of the proximate analysis for EFB and palm shells

Sample	Parameters (%)						
	Moisture	Volatile Matter	Ash Content	Fixed Carbon	Volatile Matter (Dry Basis)	Ash Content (Dry Basis)	Fixed Carbon (Dry Basis)
EFB 1	7.99	66.88	5.07	20.06	81.37	3.88	14.75
EFB 2	7.91	67.75	4.74	19.60	82.38	3.34	14.28
EFB 3	8.13	66.77	5.38	19.72	81.36	4.40	14.25
The average of EFB	8.01	67.13	5.06	19.79	81.70	3.87	14.43
Palm Shell 1	10.57	67.15	1.25	21.03	84.13	-2.20	18.07
Palm Shell 2	10.53	67.46	1.31	20.70	84.49	-2.11	17.61
Palm Shell 3	10.51	66.89	1.25	21.35	83.74	-2.22	18.47
The average of Palm Shell	10.54	67.17	1.27	21.03	84.12	-2.18	18.05

Moisture

Palm shells have a higher moisture content (ranging from 10.51% to 10.57%) than EFB shells (ranging from 7.91% to 8.13%). The moisture content in fuel significantly impacts the efficiency of the gasification process. Higher moisture initially requires more energy to evaporate the water before the fuel can burn and produce gas [2]. This implies that the gasification of palm shells requires more energy to remove moisture, potentially reducing the overall efficiency and lowering the quality of the gas produced. Conversely, EFB, with its lower moisture content, indicates that most of the water has been removed during drying or preheating, requiring less energy to evaporate water during gasification. This enhances thermal efficiency, allowing faster and more efficient combustion and more gas production. research by Havilla *et al.* [17] indicates that reducing the moisture content in biomass fuels enhances their gasification efficiency, as it minimizes the energy required for moisture evaporation, thereby improving the overall process efficiency and gas yield**.**

Volatile matter

The high volatile matter contents in EFB (66.77% - 67.75%) and palm shell (66.89% - 67.46%) suggest that both materials have good potential for producing energy-rich gas during gasification. The small difference in volatile matter content between EFB and palm shells indicates that both types of biomasses have similar combustion properties and can be effectively used in gasification. Recent research by Munoz *et al.*, supports that volatile matter is a key parameter influencing the gasification behavior, with higher volatile matter improving gas yields [18]**.**

Ash content

The ash content in EFB ranges from 4.74 to 5.38%, which is higher than that in palm shell, ranging from 1.25 to 1.31%. The ash content is the portion of the fuel that remains as residue and does not burn. A higher ash content results in more residue during gasification, which can clog the reactor and reduce process efficiency [19]. EFB, with its higher ash content, may produce more residue during gasification, requiring more maintenance to clean the reactor. On the other hand, the lower ash content in the palm shell makes it more suitable for efficient gasification, as it produces less residue for management. Studies by Gao et al, show that biomass with lower ash content tends to improve the stability and efficiency of gasification reactors [19].

Fixed carbon

The fixed carbon content in the EFB ranged from 19.60% to 20.06%, whereas in the palm shell, it ranged from 20.70% to 21.35%. Compared with volatile matter, fixed carbon is a component of fuel that burns more slowly and plays a crucial role in producing char and heat during gasification [20]. With a slightly higher fixed carbon content, palm shells can produce more heat during gasification, which can increase the reactor temperature and overall process efficiency [21]. Conversely, while EFB has a lower fixed carbon content, it still functions in gasification but may not be as efficient as palm shell in terms of heat production and reactor temperature [22] Recent studies by Mutuse *et al*. [23], highlight that a balanced fixed carbon-to-volatile matter ratio enhances both the heat generation and the carbonization process in gasification.

Volatile matter, ash content, and fixed carbon (dry basis)

On a dry basis, EFB has volatile matter contents ranging from 81.36% to 82.38%, ash contents ranging from 3.34% to 4.40%, and fixed carbon contents ranging from 14.25% to 14.75%, whereas palm shell has higher volatile matter contents ranging from 83.74% to 84.49%, very low ash contents ranging from -2.22% to -2.11%, and fixed carbon contents ranging from 17.61% to 18.47%. The dry basis calculation provides a clearer picture of the fuel potential without moisture influence [24], showing that palm shell has greater volatile matter and fixed carbon contents than EFB does. This finding supports better gasification efficiency with more gas production and higher reactor temperatures while reducing ash residue, making palm shell more efficient in gasification than EFB. Recent studies by Hardianto *et al.* [25] have shown that fuel composition on a dry basis is a more accurate indicator of gasification potential, particularly in terms of yield and reactor performance.

The analysis results indicate that the dry ash content in palm kernel shells is negative. Despite conducting three repetitions, the results remained consistent, suggesting that this phenomenon is not due to measurement errors but reflects the thermal characteristics of the material. This phenomenon can be explained through several scientific factors, supported by the following theories: *Volatility of Inorganic Compounds:* During heating, certain inorganic elements in palm kernel shells, such as potassium (K), sodium (Na), chlorine (Cl), and metal carbonates like calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), can volatilize. These compounds tend to evaporate at high temperatures, leading to the loss of most inorganic components that would otherwise contribute to ash formation. Consequently, the remaining ash after combustion is less than the initial biomass sample weight. This aligns with research by Ghafar *et al.*, which revealed that during heating or pyrolysis of palm kernel shells at high temperatures, the release of various volatile compounds occurs, including phenol, acetic acid, and octadecanoic acid [26]; *Reduction of Metal Oxide Compounds:* The reduction of metal oxide compounds in biomass also affects the amount of residual ash. Some oxides in biomass can undergo reduction reactions during combustion, transforming into gaseous forms or other volatile compounds. For instance, metal carbonates like $CaCO_3$ and $MgCO_3$ can decompose into evaporated CO_2, thereby reducing the remaining ash after combustion. This phenomenon is common in biomass with certain mineral contents, such as palm kernel shells, where the heating process can significantly alter their chemical structure [27]; *Ash Calculation Normalization Method:* The dry ash content is calculated using a method based on the initial sample weight. If most inorganic components volatilize, the remaining ash weight is less than the initial reference value. In extreme cases, this normalization can result in a negative value, even though a physical ash residue remains. This explanation is supported by the ash characterization theory in research by Puri *et al.* [28], which states that ash calculations can yield negative values if significant volatilization occurs.

Based on thermogravimetric analysis (TGA) results shown in **Table** 2, the main phases during the heating process reflect the high volatility characteristics of palm kernel shells. In the initial phase (0–90 minutes), mass loss occurs due to moisture evaporation, approximately 10.77%. Then, in the main volatilization phase around 180 minutes, a significant weight decrease occurs due to the release of volatile substances, about 67.16%, indicating that most organic components have transformed into gas. Next, in the carbonization phase between 200–240 minutes, carbon decomposition occurs, but the remaining ash is minimal. Finally, in the last phase after 300 minutes, weight loss nearly stops, indicating that most biomass has decomposed into gas, leaving a very small amount of ash.

Table 2. Data on the weight loss percentage of EFB and palm shell

Time (min)	Weight Loss (%)							
	EFB 1	EFB 2	EFB 3	The average of EFB	Palm Shell 1	Palm Shell 2	Palm Shell 3	The average of Palm Shell
00.00	0	0	0	0.00	0.0	0	0	0.00
33.33	3	3	3	3.00	3.0	3	3	3.00
66.33	9	9	9	9.00	10.5	10	10	10.17
100.00	9	9	9	9.00	10.5	10	10	10.17
133.33	75	76	75	75.33	78.0	79	78	78.33
166.67	80	81	80	80.33	82.0	82	81	81.67
200.00	84	86	85	85.00	86.0	88	85	86.33
233.33	94	95	95	94.67	99.0	99	99	99.00

Overall, both palm shell and EFB have characteristics that support gasification. A palm shell, with a slightly higher moisture content, lower ash content, and greater amount of fixed carbon, has better potential for efficient gasification. This is because palm shells generate less ash residue, more volatile gas, and more heat from fixed carbon. On the other hand, EFB has a relatively high ash content, which can reduce the gasification efficiency by increasing the residue and clogging potential in the reactor. However, with a high volatile matter content, EFB can still produce a significant amount of gas. With proper handling, EFB can also be an effective fuel for gasification. Recent reviews by Shahlan *et al.* [29], This study evaluates the thermal and physical properties of EFB, palm shell, and fiber as gasification fuels, providing insights into their combustion rates and heating values.

Thermogravimetric analysis (TGA)

Percentage of weight loss over time

There are two types of raw materials: EFB and palm shells. These parameters were tested to determine their weight loss during the heating process, as shown in Table 2. The data presented here clearly indicate that at 33.33 minutes, the EFB experienced a weight loss of 3%. This weight loss increased gradually to approximately 75.33% at 133.33 minutes. The rate of weight loss subsequently slowed, reaching 85% at 200 minutes, and eventually stabilized at approximately 94.67% at 233.33 minutes. The rapid weight reduction initially (up to 133.33 minutes) indicates moisture evaporation and volatile matter release, whereas the stabilization at the end suggests that most volatile components have decomposed, leaving residual carbon. the study "Thermal Degradation Behavior and Chemical Kinetic Characteristics of Biomass Pyrolysis Using TG-DTG-DTA Techniques" by El-Sayed *et al.* [30], investigates the thermal degradation of various biomass types, highlighting the stages of moisture evaporation, volatile release, and stabilization during pyrolysis.

The patterns of the palm shells were similar to those of the EFB but with slight differences. At 33.33 minutes, the weight loss was also 3%, but it continued to increase, reaching 78.33% at 133.33 minutes. At 200 minutes, the weight loss was 86.33%, and it stabilized at approximately 99% at 233.33 minutes, which was slightly greater than that of EFB. The addition of palm shells resulted in greater total weight loss, especially after 133.33 minutes, where volatility and decomposition processes occurred more optimally. Recent research by Ghafar *et al.* [31], indicate that the thermal characteristics of palm shells, showing that the decomposition process begins at around 130°C, with significant release of moisture and volatile materials at higher temperatures.

Greater and faster weight loss indicates greater efficiency in removing moisture and volatiles, which are crucial early stages in gasification [29]. Compared with palm shells, EFB, with a slower rate of weight reduction after a certain point, may require more energy to evaporate moisture and decompose volatiles. On the other hand, palm shells, with weight loss approaching 100%, indicate that this material is more prepared for gasification, as most volatile components have decomposed, leaving more energy-rich residual carbon. The study *"Thermogravimetric Analysis of Palm Shell Solid Waste"* by investigating the thermal degradation properties of palm shell solid waste, highlighting its efficient weight loss and volatile release during gasification [31]. Therefore, palm shells appear to be more efficient for gasification, producing more gas with higher energy, whereas EFB requires additional drying and heating steps to reach optimal conditions.

Based on the analysis presented in **Table** 2, the percentage of mass loss between empty fruit bunches (EFB) and palm kernel shells (PKS) does not show a significant difference. Theoretically, PKS have a harder structure compared to EFB, making them expected to be more resistant to combustion and decomposition. However, the results of this test can be explained by several factors, such as moisture content, chemical composition, particle size, and combustion conditions, which affect the combustion rate and mass loss of these two types of biomasses: *Moisture Content and Humidity*: The moisture content in biomass influences the combustion rate and weight loss. If EFB has a higher moisture content compared to PKS, the drying process during combustion will absorb some of the energy that should be used for the combustion process itself, thereby affecting the rate of weight loss. Research by Kuswa *et al.* [32] indicates that the moisture content in palm oil biomass can affect combustion efficiency and weight loss.; *Chemical Composition and Calorific Value*: The chemical composition of EFB and PKS differs, affecting the calorific value and combustion efficiency. Although PKS are harder, their chemical composition may allow for more efficient combustion, resulting in no significant difference in weight loss compared to EFB. Research by Kuswa *et al.* [32] shows that the chemical composition of palm oil biomass affects the calorific value and combustion efficiency.; *Physical Structure and Particle Size*: The size and physical structure of biomass influence the combustion rate. If EFB particles are smaller or their structure is more flammable, the combustion process can proceed faster, resulting in no significant difference in weight loss compared to PKS. Research by Riaza *et al.* [33] indicates that biomass particle size affects the combustion rate and weight loss.; *Combustion Conditions:* Factors such as combustion temperature, oxygen availability, and combustion time also affect the rate of weight loss. If combustion conditions are adjusted so that both types of biomasses burn with similar efficiency, their weight loss will also be similar. Research by El-Sayed *et al.* [34] shows that combustion conditions affect the combustion efficiency and weight loss of biomass.

Relationship between temperature and time

The relationship between time and the average temperature of two materials, namely, EFB and palm shell, during the heating process illustrates how the temperature of both materials increases over time. This process includes several distinct stages, such as initial heating, temperature increase, cooling, and temperature fluctuations in the final stages. The temperature data from EFB and palm shell are shown in **Table** 3.

Table 3. Data on Temperature of EFB and palm shell

Time (min)	Temperature (°C)							
	EFB 1	EFB 2	EFB 3	The average of EFB	Palm Shell 1	Palm Shell 2	Palm Shell 3	The average of palm shells
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33.33	100.00	100.00	100.00	100.00	100.00	100.00	95.00	98.33
66.33	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	120.00	120.00	120.00	120.00	130.00	130.00	125.00	128.33
133.33	930.00	940.00	940.00	936.67	930.00	920.00	940.00	930.00
166.67	750.00	750.00	750.00	750.00	760.00	760.00	760.00	760.00
200.00	580.00	580.00	580.00	580.00	590.00	590.00	580.00	586.67
233.33	700.00	700.00	700.00	700.00	705.00	705.00	700.00	703.33

Table 3 provide information on how the two materials respond to the thermal process, which is crucial in applications such as gasification, where temperature and time affect the efficiency and outcomes of the process.

Initial Heating Stage (0-66.33 minutes): At the start of the experiment (0 minutes), the average temperature of both materials was 0°C, indicating that the materials had not yet been heated. At 33.33 minutes, the average temperature of the EFB reached 100°C, whereas the temperature of the palm shell reached 98.33°C. This shows that both materials experiences nearly identical temperature increases. By 66.33 min, the average temperature of both materials had stabilized at approximately 100°C. At this temperature, drying of the materials begins, with moisture in the EFB and palm shells starting to evaporate. This drying process is important because gasification requires relatively dry fuel to avoid energy waste from water evaporation, which can reduce overall efficiency [35]. Studies such as "Effects of Gasification Temperature and Steam/Carbon (S/C) Ratio" by Mai *et al.* [36], highlight how controlling drying and initial heating stages can significantly influence gasification efficiency. Similarly, "Upgrading Process of Palm Empty Fruit Bunches as Alternative Solid Fuel" by Hardianto *et al.* [37], discusses the importance of pre-treatment steps like drying to enhance fuel quality and overall performance in gasification processes.

Volatile Formation and Initial Combustion Stage (100–133.33 minutes): At temperatures between 120°C and approximately 930°C, thermal decomposition of the organic materials in the EFB and palm shell occurs. Within this temperature range, volatile components (light gases such as CO, H_2, and methane) begin to form and are released. At approximately 900°C, gasification becomes effective, with the remaining carbon solid (char) starting to react with the gasification agents (e.g., air, steam, or oxygen) to form synthesis gas (syngas). This stage is crucial for syngas production, as supported by findings in "Investigation of a Biomass Gasification System Based on Energy and Exergy Analysis" by Kocer *et al.* [38], which emphasizes the critical role of volatile release and thermal decomposition in optimizing syngas yields during gasification.

Char Combustion Stage (133.33–200 minutes): The temperature reaches a peak of 936.67°C for the EFB and 930.00°C for the palm shell. These high temperatures represent optimal conditions for gasification reactions, particularly the combustion of the remaining char from the fuel. At these temperatures, the main reactions involve the formation of CO and H_2 from the reaction of carbon with CO_2 and H_2O. The quality and quantity of the produced gas are significantly influenced by these high temperatures, with the conversion efficiency improving as the temperature increases. Research such as "Process Development of Oil Palm Empty Fruit Bunch Gasification by Air Fluidized Bed Reactor" by Shahlan *et al.* [39], highlights how achieving these optimal conditions maximizes gasification performance and minimizes by-product formation.

Cooling and final temperature fluctuation stage (166.67–233.33 min): After the peak temperature is reached, the temperature begins to decrease, indicating the end of the main gasification stage. However, there was a subsequent temperature increase at 233.33 minutes, which may have been due to fluctuations in the system or adjustments in the experimental conditions. In industrial gasification operations, consistent temperature control is crucial to ensure efficient gasification without disrupting gas production [40]. The study "Effects of Gasification Temperature and Equivalence Ratio on Performance and Tar Generation in Air Fluidized Bed Gasifier" by Saleh and Samad [41], underscores the importance of maintaining stable temperatures during cooling stages to prevent inefficiencies and maintain consistent syngas quality.

Activation energy

The activation energy (Ea) is a crucial parameter in understanding the rate of chemical reactions, including the biomass gasification process, such as with EFB and palm shells. In this context, the activation energy provides insight into how much energy is required to initiate the devolatilization process, which is the initial stage of gasification where organic material breaks down into simpler gases and solids (char).

The activation energy (Ea) is calculated via the Arrhenius equation, as expressed in Eq. 1 and Eq. 2 [42]. The results from the thermogravimetric analysis (TGA) are shown in Table 3, which illustrates the temperature changes in the EFB and palm shell over time. The temperature in Kelvin (K) from the TGA data is used to calculate 1/T for each data point. Assuming that the rate constant (k) is directly proportional to temperature, temperature is used as a substitute for k, allowing the activation energy to be determined via the data in Figure 1.

Figure 1 shows the linear regression lines used to calculate the activation energy. The red line represents the regression for EFB, whereas the blue line represents the regression for Palm Shell. The slope of each line is used to determine the activation energy for the respective processes. The graph of ln(T) vs. 1/T for both EFB and palm shell exhibits a strong linear correlation, confirming that the linear regression method is a valid approach for estimating the activation energy on the basis of the available data. From the graph, the linear equation for EFB is derived as follows:

$$y = -539.2x+7.435 \tag{5}$$

Thus, the activation energy for the EFB is 4482.19 J/mol. Moreover, the linear equation for the palm shell is as follows:

$$y = -539.51x+7.4357 \tag{6}$$

Thus, the activation energy for the palm shell is 4484.97 J/mol.

These values indicate that the energy required to initiate the devolatilization process in the EFB and palm shell is nearly the same, with slight differences, likely due to the varying chemical and physical compositions of the two biomass types. The relatively low activation energy (in the range of 4482--4485 J/mol) suggests that both types of biomasses are quite reactive and do not require significant energy to begin the devolatilization process.

This finding is supported by several studies. For instance, the study "Kinetic Study on Pyrolysis and

Combustion of Palm Empty Fruit Bunch" by Surahmanto *et al.* [43], investigates the pyrolysis kinetics of palm empty fruit bunch, emphasizing the low activation energy and its relevance for thermal processes. Additionally, "Determination of Kinetic and Thermodynamic Parameters of Biomass Gasification with TG-FTIR and Regression Model Fitting" by Zsinka *et al.* [44], provides a comprehensive approach to determining activation energy in biomass gasification, confirming that regression methods are effective for estimating activation energies similar to the methods applied in this study.

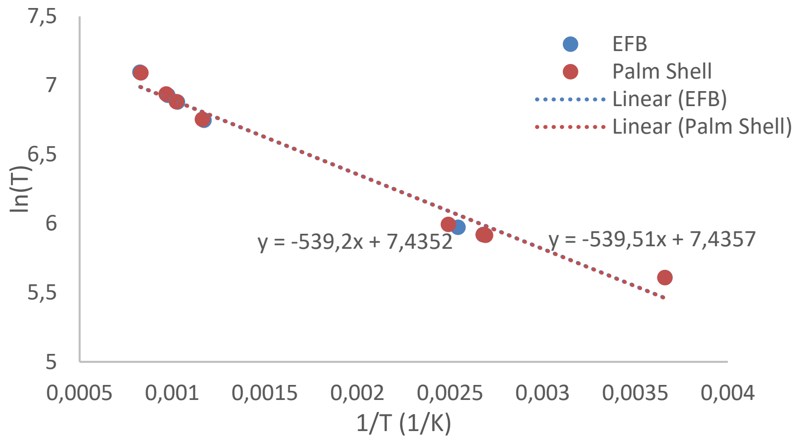

Figure 1. Arrhenius plot for determining the activation energy

Gasification process of the EFB and palm shells

EFB and palm shell were used as raw materials in the gasification process at 600°C. The syngas produced was analyzed via gas chromatography. The analysis parameters included the composition of the gases produced (CO, H_2, CH_4, CO_2, and N_2), the percentage of combustible gases (% CG) and noncombustible gases (% NCG), and the ratio between combustible and noncombustible gases, which was also calculated to determine the combustion efficiency of each material. The data are presented in Figure 2.

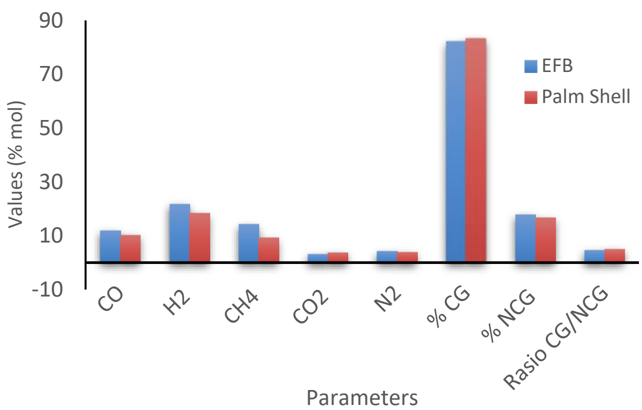

Figure 2. Comparison of the Gas Composition and Combustion Ratios for the EFB and Palm Shell at 600 °C

Gas composition

EFB produces more CO (11.93%) than Palm Shell does (10.33%). This indicates that EFB tends to generate more carbon monoxide during gasification. The hydrogen gas (H_2) content is greater in the EFB (21.86%) than in the palm shell (18.37%), which could indicate that the EFB produces more energy from hydrogen gas. The methane (CH_4) concentration in the EFB (14.22%) is significantly higher than that in the palm shell (9.21%), which may influence the difference in energy efficiency. Carbon dioxide (CO_2) is slightly higher in the palm shell (3.72%) than in the EFB (3.17%), indicating a slightly higher oxidation level in the palm shell. The nitrogen (N_2) content in the EFB (4.22%) was slightly greater than that in the palm shell (3.89%).

Recent studies further support these findings. For instance, the research *"Valorization of Palm Empty Fruit Bunch Waste for Syngas Production Through Gasification"* by Apriyanti *et al.* [45] indicates that gasification at 550°C produces syngas with 3.4% H_2, 29.22% CO, 22.64% CH_4, and 1.1% carbon dioxide (CO_2).

Combustible ratio

The number of combustible gases (% GC) is slightly greater in the palm shell (83.28%) than in the EFB (82.14%), indicating that the palm shell is slightly more efficient at producing burnable gases. Conversely, noncombustible gases (% NGC) are more common in the EFB (17.86%) than in the palm shell (16.72%). The ratio between combustible and noncombustible gases (CG/NCG ratio) is greater in the Palm shell (4.98) than in the EFB (4.6), suggesting that the Palm shell is superior in terms of combustion efficiency.

Recent studies further support these findings. For instance, the study *"Catalytic Gasification of Oil Palm Empty Fruit Bunch by Using Indonesian Bentonite as the Catalyst"* reports a CG/NCG ratio of 9.72, highlighting the effectiveness of bentonite catalysts in enhancing the production of combustible gases during gasification [46]. Overall, both EFB and palm shell have significant potential as feedstocks for the production of renewable energy through pyrolysis or gasification processes. EFB tends to produce more combustible gas in absolute terms, whereas Palm Shell has a slightly higher efficiency ratio. The choice of feedstock between the two may depend on the specific energy process requirements, with a greater focus on the quantity or efficiency of the produced gas.

CONCLUSION

This study demonstrated the potential of empty fruit bunches (EFB) and palm kernel shells as feedstocks for gasification to produce renewable energy. Through thermogravimetric analysis and kinetic evaluation, palm kernel shells were identified as a more efficient fuel due to their higher fixed carbon content, lower ash residue, and superior gasification efficiency. However, EFB exhibited notable gas production, suggesting its potential with pre-treatment to reduce ash content. The findings underscore the importance of optimizing biomass gasification processes to improve energy yield and reduce environmental impact. This research contributes valuable insights into utilizing agricultural waste for sustainable energy solutions, aligning with efforts to advance eco-friendly technologies.

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