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Characterization of Biochar Produced From Oil Palm Fronds Using The Pyrolysis Method

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ABSTRACT

Oil palm fronds are one of the solid wastes generated in large quantities from oil palm plantation activities. The increasing area of oil palm plantations has led to a higher production of biomass waste, including oil palm fronds, which are still not utilized optimally. One alternative utilization is converting oil palm fronds into biochar through the pyrolysis process. This study aims to characterize biochar produced from oil palm fronds using a retort pyrolysis method and determine its elemental composition through CHNS/O analysis. The research was conducted using a retort pyrolysis method at temperatures ranging from 350°C to 400°C. The resulting biochar was analyzed using a CHNS/O Elemental Analyzer to determine the contents of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S). The data obtained were analyzed descriptively to characterize the elemental composition of the produced biochar. The CHNS/O analysis showed that the biochar contained 71.85% carbon, 3.75% hydrogen, 21.93% oxygen, 1.68% nitrogen, and 0.33% sulfur. The results indicate that oil palm fronds can be effectively converted into carbon-rich biochar through the retort pyrolysis method. This biochar has potential applications in sustainable biomass management, soil improvement, and environmental remediation.

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INTRODUCTION

Indonesia is currently recognized as the largest palm oil producer in the world. The continuous expansion of oil palm plantations has significantly contributed to national economic growth, employment opportunities, and the development of downstream palm oil industries. However, the rapid growth of this sector also generates a substantial amount of biomass residues, including oil palm fronds, trunks, empty fruit bunches, fibers, and shells. Among these residues, oil palm fronds (OPF) are produced continuously through routine pruning activities and are often left in plantation areas without further utilization. It has been estimated that one hectare of oil palm plantation can generate approximately 6.3 tons of fronds annually, indicating a considerable biomass resource that remains underutilized.(Hwong et al., 2022)

Oil palm fronds contain high levels of lignocellulosic compounds consisting primarily of cellulose, hemicellulose, and lignin. These components make oil palm fronds a promising feedstock for thermochemical conversion processes. The relatively high lignin content is particularly advantageous because lignin contributes to the formation of stable carbon structures during pyrolysis. Therefore, converting oil palm fronds into value-added products such as biochar can provide an effective strategy for biomass waste management while simultaneously increasing the economic value of plantation residues.(Sifat et al., 2022)

Biochar is a carbon-rich material produced through the thermal decomposition of biomass under oxygen-limited conditions. Owing to its stable carbon structure and porous properties, biochar has received considerable attention for agricultural and environmental applications. Previous studies have shown that biochar can improve soil quality, enhance nutrient retention, and contribute to carbon sequestration, making it a promising material for sustainable biomass utilization and environmental management (Puspita, 2021; Yaashikaa et al., 2020; Khan et al., 2024; Tuti Ariani Bawamenewi et al., 2025; Hoque et al., 2025).

The characteristics and quality of biochar are highly dependent on both the feedstock properties and the pyrolysis conditions employed during production. Among the various process parameters, pyrolysis temperature is one of the most influential factors affecting the physicochemical properties of biochar. Higher pyrolysis temperatures generally increase carbon content and aromaticity while decreasing hydrogen and oxygen contents. These changes significantly influence the stability, adsorption capacity, and overall performance of biochar. Consequently, understanding the elemental composition of biochar produced under selected pyrolysis conditions is essential for producing biochar with desirable properties(Prasetiyo et al., 2020)

Previous studies have reported that pyrolysis conditions may influence the physicochemical characteristics of biochar, including its elemental composition and stability. These findings provide important background information regarding biochar production. However, studies specifically focusing on the CHNS/O elemental characterization of oil palm frond biochar produced using a retort pyrolysis system remain limited. Therefore, further investigation is required to provide detailed information regarding the elemental composition of this biomass-derived material (Ali et al., 2025)

Several studies have investigated the production and characterization of biochar derived from oil palm biomass. Previous research demonstrated that biochar produced from oil palm fronds possesses favorable chemical characteristics and considerable potential for agricultural applications. In addition, the utilization of oil palm biomass for biochar production has been reported to support carbon sequestration and sustainable waste management practices. Several studies have investigated the production and characterization of biochar derived from oil palm biomass and reported its potential for agricultural and environmental applications. Nevertheless, information regarding the CHNS/O elemental characteristics of oil palm frond biochar produced using a retort pyrolysis system remains limited. In particular, studies providing detailed elemental composition data, including carbon, hydrogen, nitrogen, sulfur, and oxygen contents, are still scarce. Therefore, this study aims to characterize oil palm frond biochar produced by a retort pyrolysis system using CHNS/O elemental analysis to provide fundamental information on its chemical properties and potential utilization (Reynaldi et al., 2024)(Septyani & Zamzami, 2025)

Therefore, this study aims to characterize biochar produced from oil palm fronds using a retort pyrolysis method at temperatures ranging from 350–400°C. The characterization was conducted using CHNS/O elemental analysis to determine the composition of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) in the resulting biochar. The findings of this study are expected to provide scientific information regarding the utilization of oil palm frond biochar as a sustainable biomass-based material and support future applications in agriculture, environmental management, and carbon sequestration.

METHOD

This study used oil palm fronds (Elaeis guineensis Jacq.) as the raw material for biochar production. The oil palm fronds were collected from oil palm plantation areas in North Sumatra, Indonesia. Prior to the pyrolysis process, the fronds were cleaned to remove dirt and other impurities attached to the surface. The biomass was then cut into smaller pieces with a length of approximately 5 cm to facilitate handling and improve heat transfer during carbonization. Subsequently, the prepared biomass was air-dried to reduce moisture content before being subjected to the pyrolysis process. Oil palm fronds were selected because they are one of the most abundant biomass residues generated from oil palm plantation management activities and contain considerable amounts of cellulose, hemicellulose, and lignin, which are suitable for biochar production through thermochemical conversion processes(Promraksa & Rakmak, 2020)**.** A total of 22 kg of oil palm fronds were collected and prepared as feedstock for this study. Approximately 1 kg of dried biomass was used for each pyrolysis run in the retort reactor.

Biochar production was carried out using a retort pyrolysis system under limited oxygen conditions. Approximately 1 kg of dried oil palm fronds was placed inside the retort reactor and heated externally. The pyrolysis process was conducted at temperatures ranging from 350°C to 400°C. This temperature range was selected because it is considered sufficient to promote thermal decomposition of lignocellulosic components while enhancing carbon enrichment in the resulting biochar. During the process, temperature was monitored regularly to maintain stable operating conditions and ensure uniform carbonization. After completion of the pyrolysis process, the reactor was allowed to cool naturally to room temperature before the biochar was collected and stored in airtight containers. The use of a retort pyrolysis system provides better control over oxygen availability during carbonization and contributes to the production of biochar with more stable physicochemical characteristics(Mohamed & Yusup, 2021)(Mevira Setiawan et al., 2025)

The physicochemical properties of biochar are strongly influenced by both feedstock characteristics and pyrolysis operating conditions. Variations in pyrolysis temperature may affect carbon concentration, pore development, ash content, and surface functional groups, which ultimately determine the agronomic and environmental performance of biochar. Therefore, careful control of pyrolysis conditions is essential to produce biochar with desirable characteristics. Previous studies have demonstrated that feedstock type and pyrolysis temperature are among the most important factors governing biochar quality and stability(Lataf et al., 2022).

Table 1. Research Parameters

No	Description	Explanation
1	Feedstock	Oil palm fronds
2	Biomass condition	Air-dried oil palm fronds
3	Sample size	Approximately 5 cm
4	Sample weight	22 kg
5	Feedstock per pyrolysis run	Approximately 1 kg
6	Pyrolysis method	Retort pyrolysis
7	Pyrolysis temperature	350°C –400°C
8	Oxygen condition	Limited oxygen
9	Analytical method	CHNS/O Elemental Analyzer
10	Observed parameters	Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), and Sulfur (S)
11	Replication of analysis	Two replications

The biochar produced from the pyrolysis process was subsequently characterized through elemental analysis using a CHNS/O Elemental Analyzer. Prior to analysis, the biochar samples were crushed and ground into fine particles to obtain homogeneous samples and improve measurement accuracy. The analysis was performed to determine the percentage composition of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) contained in the biochar. Elemental characterization is commonly used to evaluate biochar quality because the elemental composition reflects the degree of carbonization that occurs during the pyrolysis process. In general, higher carbon content indicates a more stable biochar structure, while lower hydrogen and oxygen contents suggest a greater degree of thermal decomposition and aromatic carbon formation (Omar et al., 2018; Marihot Sianipar et al., 2024).

Before elemental analysis, the produced biochar samples were stored in airtight containers to prevent moisture absorption from the surrounding environment. The samples were then ground and sieved to obtain a more uniform particle size. Approximately 2–3 mg of each sample was used for CHNS/O analysis according to the operational procedure of the instrument. To ensure data reliability, the analysis was performed under controlled laboratory conditions, and the resulting values were reported as percentages on a dry-weight basis. The elemental composition obtained from the analysis was subsequently used to evaluate the degree of carbonization and the quality of biochar produced from oil palm fronds. Similar procedures have been widely applied in biochar characterization studies to assess the chemical properties of biomass-derived carbon materials(Promraksa & Rakmak, 2020; Omar et al., 2018).

Elemental characterization is widely applied in biochar research because it provides comprehensive information regarding the degree of carbonization and potential applications of the resulting material. The elemental composition of biochar is closely associated with its stability, surface reactivity, adsorption capacity, and environmental performance. Recent studies have highlighted that CHNS/O analysis remains one of the most reliable methods for evaluating biochar quality and understanding the influence of pyrolysis conditions on biomass-derived carbon materials (Varkolu et al., 2025)

The data obtained from elemental analysis were expressed as percentages on a dry-weight basis. The results were tabulated and analyzed descriptively to determine the characteristics of biochar produced from oil palm fronds under the selected pyrolysis conditions. Furthermore, the elemental composition obtained in this study was compared with findings reported in previous studies involving biochar derived from oil palm biomass. This comparison was conducted to evaluate the elemental characteristics of biochar produced using the retort pyrolysis process and to assess the suitability of the resulting biochar for agricultural and environmental applications. The interpretation of the results focused on describing the elemental characteristics and potential quality of biochar produced under the selected pyrolysis temperature range.

RESULTS AND DISCUSSION

Biochar Production Process

The production of biochar from oil palm fronds was successfully carried out using a retort pyrolysis system at temperatures ranging from 350–400°C. During the pyrolysis process, the biomass underwent significant physical and chemical transformations. Initially, the oil palm fronds exhibited a fibrous texture and light brown color. As the temperature increased, moisture and volatile compounds were gradually removed, resulting in the formation of a black solid product with a more brittle structure. These physical changes indicate that thermal decomposition occurred effectively and that the lignocellulosic components within the biomass were converted into carbon-rich material.

Figure 1. Retort Pyrolysis Reactor Used In This Study

The retort pyrolysis system provided a controlled environment that limited direct contact between oxygen and biomass during carbonization. This condition is important because excessive oxygen exposure may lead to complete combustion and reduce biochar yield. Tomczyk et al. (2020), reported that oxygen availability and pyrolysis temperature are among the most influential factors affecting biochar quality and stability. Controlled pyrolysis systems generally promote greater carbon retention and produce biochar with improved physicochemical characteristics.

Following the pyrolysis process, the resulting biochar exhibited a black color and porous structure. The formation of pores occurred as volatile compounds escaped from the biomass matrix during thermal decomposition. These pores increase the surface area of biochar and contribute to its adsorption capacity, nutrient retention, and interaction with water molecules. Dayoub et al. (2024) explained that pore development is one of the most important characteristics influencing the effectiveness of biochar when applied to soil and environmental systems.

The physical appearance of the produced biochar suggests that the selected pyrolysis temperature was sufficient to promote carbonization while maintaining structural integrity. Biochar with a porous structure is generally considered advantageous because it provides more active sites for nutrient retention and adsorption processes. Therefore, the physical characteristics observed in this study indicate that oil palm fronds can be effectively converted into biochar through the retort pyrolysis method.

During pyrolysis, moisture and volatile substances contained in the biomass were gradually removed. As a result, the mass of the material decreased and its physical appearance changed significantly. Similar observations have been reported in previous studies involving biochar production from agricultural residues, where biomass undergoes substantial structural and compositional changes during thermal treatment. The resulting biochar obtained from the pyrolysis process is presented in Figure 2.

Figure 2. Biochar Produced From Oil Palm Fronds

Based on visual observation, the resulting biochar exhibited a dark black color with a relatively porous structure. The black coloration indicates that carbonization occurred successfully during pyrolysis. In addition, the biochar appeared lighter and more brittle than the original biomass. These characteristics are commonly observed in biochar derived from lignocellulosic materials and indicate that significant chemical and structural transformations occurred during thermal decomposition.

The porous structure observed in the biochar was formed as volatile compounds escaped from the biomass matrix during heating. The development of pores is considered beneficial because it increases the surface area of the material. This characteristic may enhance the ability of biochar to retain water, nutrients, and other substances when applied to soil. Therefore, the physical characteristics observed in this study indicate that oil palm fronds can be effectively converted into biochar through the retort pyrolysis process.

The successful production of biochar from oil palm fronds demonstrates the potential of utilizing plantation residues as value-added products. Oil palm fronds are continuously generated during plantation maintenance activities and are often left in the field. Converting this biomass into biochar not only reduces waste accumulation but also creates opportunities for producing environmentally beneficial materials.

Elemental Composition Of Oil Palm Frond Biochar

The elemental composition of biochar produced from oil palm fronds was determined using a Carbon, Hydrogen, Nitrogen, Sulfur, and Oxygen (CHNS/O) Elemental Analyzer. The analysis was conducted to evaluate the chemical characteristics of the resulting biochar and to determine the degree of carbonization achieved during the pyrolysis process. The results of the elemental analysis are presented in Table 2.

Table 2. Elemental Composition of Oil Palm Frond Biochar

Replication	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulfur (%)
1	71.52	3.82	22.11	1.64	0.31
2	72.18	3.67	21.74	1.71	0.34
Average	71.85	3.75	21.93	1.68	0.33
SD	0.47	0.11	0.26	0.05	0.02

The results indicate that carbon was the dominant element in the produced biochar, followed by oxygen, hydrogen, nitrogen, and sulfur. This composition reflects the effectiveness of the pyrolysis process in concentrating carbon while reducing the proportion of volatile components. Similar elemental distributions have been reported for biochar produced from various lignocellulosic feedstocks, where carbon becomes the dominant constituent after thermal treatment (L. Li et al., 2023).

Elemental composition is commonly used as an indicator of biochar quality because it provides information regarding the degree of carbonization and stability of the resulting material. Higher carbon content generally indicates greater stability and carbon sequestration potential, whereas oxygen-containing functional groups contribute to nutrient retention and adsorption properties (Ippolito et al., 2020).

The selected pyrolysis temperature range (350–400°C) was suitable for producing biochar with relatively high carbon content while maintaining acceptable biochar yield. At this temperature range, the decomposition of volatile compounds occurs more intensively, allowing carbon to become concentrated in the remaining solid material. Consequently, the resulting biochar tends to exhibit greater stability compared with untreated biomass.

The relatively small differences observed between the two replications, as indicated by the low standard deviation values, suggest that the biochar produced in this study had consistent characteristics. Although minor variations may occur due to biomass heterogeneity and analytical procedures, the overall results suggest that the pyrolysis process was conducted under stable operating conditions.

Carbon Content

Carbon was identified as the dominant element in the produced biochar, accounting for 71.85% of the total elemental composition. This result indicates that the pyrolysis process effectively promoted carbon enrichment within the biomass structure. During thermal decomposition, cellulose and hemicellulose degrade into volatile compounds, while lignin contributes significantly to fixed carbon formation. Consequently, carbon becomes increasingly concentrated in the remaining solid residue.

The relatively high carbon concentration obtained in this study suggests that the selected pyrolysis temperature was sufficient to enhance carbonization while maintaining the structural stability of the resulting biochar. (Tomczyk et al., 2020)reported that increasing pyrolysis temperature generally promotes carbon enrichment and the formation of more stable carbon structures. Similar findings were reported by (X. Li et al., 2023), who found that increasing pyrolysis temperature promotes carbon enrichment, enhances pore development, and improves the stability of biochar through the formation of more condensed aromatic carbon structures.

High carbon content is widely recognized as one of the primary indicators of biochar quality because it reflects the formation of stable aromatic carbon structures. These structures are more resistant to microbial decomposition and oxidation compared with the original biomass. As a result, biochar can remain in soil for extended periods and function as a long-term carbon storage material. X. Li et al. (2023) reported that carbon-rich biochar contributes significantly to carbon sequestration and may help mitigate greenhouse gas emissions through long-term carbon retention.

In addition to environmental benefits, carbon-rich biochar may improve soil quality by enhancing soil aggregation, increasing water retention, and providing suitable habitats for beneficial microorganisms. Dayoub et al. (2024) noted that biochars containing high carbon concentrations often exhibit improved physicochemical properties and enhanced performance when used as soil amendments. Therefore, the carbon content obtained in this study indicates that oil palm frond biochar has considerable potential for agricultural and environmental applications.

Hydrogen and Oxygen Contents

Hydrogen content was measured at 3.75%, while oxygen content reached 21.93%. These values provide important information regarding the degree of carbonization achieved during pyrolysis. During thermal treatment, hydrogen-containing compounds are progressively released as water vapor and volatile hydrocarbons, resulting in the formation of condensed aromatic carbon structures.

The relatively low hydrogen concentration observed in this study suggests that a considerable degree of carbonization occurred during the pyrolysis process. According to (Ippolito et al., 2020), lower hydrogen concentrations are generally associated with lower H/C ratios and greater biochar stability. Biochars with lower H/C ratios tend to exhibit greater resistance to oxidation and microbial degradation, making them more suitable for long-term environmental applications.

Tomczyk et al. (2020) also reported that decreasing hydrogen content is often accompanied by increased aromaticity within the carbon matrix. Aromatic carbon structures are considered more stable because they are less susceptible to decomposition. Therefore, the hydrogen concentration obtained in this study further supports the conclusion that the produced biochar possesses favorable characteristics for long-term utilization.

Oxygen content is primarily associated with the presence of oxygen-containing functional groups that remain after pyrolysis. Although oxygen concentration decreases as carbonization progresses, the retention of certain functional groups is beneficial because they contribute to nutrient retention, adsorption capacity, and surface reactivity. X. Li et al. (2023) emphasized that oxygen-containing functional groups influence the interaction between biochar surfaces and soil nutrients.

Furthermore, oxygen-containing functional groups contribute significantly to cation exchange capacity and adsorption performance. Ghorbani et al. (2022) explained that biochars retaining moderate oxygen concentrations often exhibit enhanced performance as soil amendments because of their increased surface reactivity. Therefore, the oxygen content observed in this study suggests that the produced biochar retained favorable functional properties despite undergoing thermal decomposition.

Nitrogen and Sulfur Content

Nitrogen content was recorded at 1.68%, while sulfur content was 0.33%. Both elements were present in considerably lower concentrations than carbon and oxygen. The relatively low nitrogen concentration may be attributed to the volatilization of nitrogen-containing compounds during thermal decomposition. As pyrolysis temperature increases, proteins and other nitrogen-containing structures are progressively degraded and released as gaseous products.

Despite its relatively low concentration, nitrogen remains important because it contributes to the nutrient value of biochar. (X. Li et al., 2023) reported that residual nitrogen retained within biochar may support nutrient cycling and microbial activity when applied to soil. Consequently, the presence of nitrogen, even in small amounts, may provide additional agronomic benefits.

The sulfur concentration observed in this study was relatively low, accounting for only 0.33% of the total elemental composition. This result is considered advantageous because excessive sulfur concentrations may contribute to soil acidification and undesirable emissions during thermal processing. (Ghorbani et al., 2022) reported that sulfur is generally present in relatively small quantities within biomass-derived biochar because a substantial portion is volatilized during carbonization.

Low sulfur concentrations are commonly associated with reduced environmental risks and improved suitability for agricultural applications. Therefore, the sulfur content obtained in this study suggests that the produced biochar can be safely utilized without causing significant sulfur-related environmental concerns. However, because this study was conducted within a single selected temperature range of 350–400°C, the findings should be interpreted as characterization results rather than evidence of temperature-dependent differences.

Implications of Biochar Characteristics

The elemental composition and physical characteristics obtained in this study demonstrate that oil palm fronds can be effectively converted into high-quality biochar through the retort pyrolysis method. The high carbon content, combined with relatively low hydrogen, nitrogen, and sulfur concentrations, indicates that carbonization occurred successfully and produced a stable carbon-rich material. The produced biochar has considerable potential for use as a soil amendment. The combination of high carbon content and porous structure may improve soil physical properties, including water retention, aeration, and aggregate stability. According to Khan et al. (2024), biochar application can enhance nutrient retention and reduce nutrient losses through leaching, thereby supporting sustainable agricultural production.

In addition to agricultural applications, the presence of oxygen-containing functional groups and porous structures may enhance the adsorption capacity of biochar toward pollutants and contaminants. Biochar has significant potential for environmental remediation because of its ability to adsorb heavy metals, organic pollutants, and excess nutrients from soil and water systems. These properties make biochar a promising material for environmental management and pollution control.

Furthermore, the utilization of oil palm fronds for biochar production provides an alternative strategy for managing plantation residues. Instead of being discarded or openly burned, oil palm fronds can be converted into value-added products with economic and environmental benefits. This approach supports sustainable biomass utilization while simultaneously reducing waste generation and promoting circular agricultural practices.

Overall, the findings of this study confirm that oil palm fronds represent a promising feedstock for biochar production. Through the retort pyrolysis method, plantation residues can be transformed into high-quality biochar with potential applications in soil improvement, carbon sequestration, and environmental remediation. These characteristics highlight the important role of oil palm frond biochar in supporting sustainable agricultural development and environmental conservation.

CONCLUSIONS

This study successfully characterized biochar produced from oil palm fronds using the retort pyrolysis method at a temperature range of 350–400°C. CHNS/O analysis revealed that the biochar was dominated by carbon (71.85%), followed by oxygen (21.93%), hydrogen (3.75%), nitrogen (1.68%), and sulfur (0.33%). The high carbon content indicates successful carbonization and suggests that the resulting biochar possesses favorable characteristics for long-term utilization.

The findings demonstrate that oil palm fronds have considerable potential as a feedstock for biochar production, transforming plantation biomass residues into a value-added product. The produced biochar may be utilized in agricultural and environmental applications, particularly as a soil amendment and a material that supports sustainable biomass management. Therefore, converting oil palm fronds into biochar represents a promising strategy for promoting sustainable resource utilization and reducing plantation biomass waste.

The findings also highlight the practical potential of converting oil palm plantation residues into value-added biochar products that can support community-based biomass waste management and sustainable agricultural practices among farmers and plantation communities. Further research is recommended to evaluate additional biochar properties, including pH, ash content, surface area, and adsorption capacity, as well as to assess its performance in agricultural and environmental applications.

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AUTHOR CONTRIBUTION

DR: Conceptualization, investigation, data collection, formal analysis, and writing–original draft preparation. SA: Supervision, methodology validation, manuscript review and editing, and project administration.

AI DISCLOUSURE STATEMENT

The author declares that artificial intelligence (AI) technology was used during the preparation of this manuscript solely to assist with translation, grammar correction, and language refinement. The manuscript was carefully reviewed and edited by the author to ensure the clarity, consistency, and accuracy of the content presented in this article.

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