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Article

Carbon Sequistration through Oil Palm Frond Biochar for CO_2 Mitigation and Land Degradation

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ABSTRACT

The increasing expansion of palm oil plantations can exacerbate climate change due to high deforestation rates and increased CO_2 emissions. This study aims to identify carbon sequestration through oil palm frond biochar as a mitigation strategy for CO_2 emissions and land degradation. This research conducted at Palm Oil Plantation on Siluman B, Labuhanbatu District. This study using a Factorial Randomized Block Design with two factors, 3 × 2, and 5 replications, resulting in 30 experimental units. The main factor is biochar A0 = No biochar, A1 = 1.5 kg, A2 = 3.0 kg. The second factor is the method of biochar application which includes B0 = Incorporation into soil, B1 = Applied on the soil surface. Biochar significantly increases soil carbon stocks by nearly double, proving its role in carbon sequestration. Application of biochar on the surface and incorporation into soil have the same efect to increase soil carbon sequistration. Biochar fundamentally improves soil fertility by increasing the Cation Exchange Capacity, total N content, and the availability of essential base cations, while lowering the C/N ratio to a more ideal level. The method of incorporating biochar into the soil proved superior for enhancing CEC, making it the recommended practice.

INTRODUCTION

Global climate change has become a significant challenge, particularly for the agriculture and deforestation sectors in tropical regions, which are major contributors to greenhouse gas emissions, especially carbon dioxide (CO_2). Palm oil is Indonesia's leading agricultural commodity and contributing significantly to the national economy through exports (Sehusman, 2023). The increasing expansion of palm oil plantations can exacerbate climate change due to high deforestation rates and increased CO_2 emissions. Land clearing for palm oil often involves the felling of tropical forests, which act as carbon sinks in the form of biomass and soil, releasing carbon into the atmosphere as CO_2. Additionally, land fires and unsustainable plantation management lead to soil degradation, reducing its capacity to store carbon and worsening the impacts of climate change.

Unsustainable palm oil plantation management, such as monoculture systems, also contributes to the decline in the land's ability to store carbon. Degraded soils have low organic matter content and are ineffective at sequestering carbon. Therefore, mitigation efforts that can be implemented include organic matter sequestration (Sari *et al*, 2017). Organic matter sequestration refers to the process of storing carbon contained in organic materials, such as plants or organic waste, into the soil or other environments to reduce the concentration of carbon dioxide (CO_2) in the atmosphere. Carbon sequestration can potentially help reduce these negative impacts and enhance the land's capacity to store carbon. Organic matter sequestration refers to the process of storing carbon contained in organic materials, such as plants or organic waste, into the soil or other environments to reduce the concentration of carbon dioxide (CO_2) in the atmosphere. This process is crucial in mitigating climate change, as it can lower CO_2 emissions, the primary greenhouse gas responsible for global warming.

One strategy for carbon sequestration is through the use of biochar from oil palm fronds. Biochar is produced through the pyrolysis of organic waste, a process of burning with limited oxygen that results in a carbon-rich, stable material (Wang *et al*, 2017). Biochar derived from oil palm fronds has the potential to reduce CO_2 emissions as it can store carbon over the long term, contributing to organic matter sequestration, and improve soil quality by enhancing soil structure and increasing organic matter content. Furthermore, biochar can increase soil's capacity to retain water and nutrients, positively impacting agricultural sustainability, including palm oil plantations. The use of biochar can also reduce land fires, which are often associated with palm oil land expansion, and help provide environmentally friendly solutions for agricultural waste management. Biochar also attributed to the intrinsic properties of biochar itself, which possesses a high surface area and is rich in negatively charged functional groups (such as carboxyl and hydroxyl). These negative charges function to attract and retain positively charged cations, including essential plant nutrients (Hidayat *et al*, 2021).

Oil palm fronds, often considered waste and typically burned, contain significant amounts of carbon and can be processed into biochar for carbon sequestration purposes. According to research, biochar from oil palm fronds contains between 28-34% organic carbon, making it a potential material to improve soil fertility and sequester carbon (Reynaldi *et al*, 2024). The use of biochar as a soil ameliorant can enhance soil quality, improve soil structure, and act as a form of sustainable environmental conservation (Nurida, 2014). Further research is needed to determine how much carbon can be sequestered in the soil, particularly in the root zone of oil palm. The quantification of organic matter sequestration is necessary because, while it is common scientific knowledge that organic materials such as biochar can store carbon in the soil, there is a crucial need for the precise measurement of the exact amounts. Once this quantity is known, it is beneficial for assessing whether a method, such as the use of biochar, is genuinely effective and cost-efficient in relation to the required labor and expenses. Furthermore, carbon stored in the root zone interacts directly with oil palm roots (Haider *et al*, 2022). Research is required to ascertain whether this addition of carbon yields positive impacts especially for improving soil structure and nutrient availability) or, conversely, has negative effects on the growth and productivity of the oil palm (Amrullah, 2020).

This study aims to identify carbon sequestration through oil palm frond biochar as a mitigation strategy for CO_2 emissions and land degradation in palm oil plantations. It seeks to explore the potential of oil palm frond biochar in mitigating CO_2 emissions and improving soil quality in palm oil plantations, thus contributing to more sustainable and environmentally friendly land management practices

MATERIALS AND METHODS

Time and Place

This research will be conducted from January to August 2025 at Palm Oil Plantation on Siluman B, Labuhanbatu District.

Research Methodology

This study is a field experiment using a Factorial Randomized Block Design with two factors, 3 × 2, and 5 replications, resulting in 30 experimental units. The main factor is the dose of oil palm frond biochar application, which consists of 5 levels as follows, A0 = No biochar, A1 = 1.5 kg, A2 = 3.0 kg. The second factor is the method of biochar application on oil palm fronds, which includes B0 = Applied to the root zone, B1 = Applied on the soil surface.

Soil Parameter

Intact and disturbed soil samples from each treatment were air-dried for laboratory analysis, which includes the chemical, biological, and physical properties of the soil. The soil analyses conducted are Organic C using the Walkley and Black method, Bulk density using the Volumetric method, CEC, and macro nutrients N, K using a spectrophotometer method. The soil samples that were collected were air-dried and then sieved through a 0.5 mm K analysis, and a 0.25 mm sieve for Organic C analysis. For the preparation of Bulk Density samples, undisturbed ring samples were used.

Organic Matter Sequestration Calculation

Estimation of organic matter sequestration can be carried out by calculating the amount of carbon stored in the soil, especially organic carbon, using various methods that involve soil sampling and laboratory analysis. One of these methods includes measuring the levels of organic carbon (C-Organic) and bulk density (BD). Subsequently, the calculation of bulk density or mass density (BD) is expressed as mass per unit volume of soil (g/cm^3 or ton/m^3) (Harahap et al, 2021).

BD (g/cm^3) = (*Wt - Wg) (1 - MFf) / 4 x Vr* (ml) ……(1)

Wt = Total weight of air-dried soil (g)
Wg = Weight of gravel (g)
MFf = Moisture factor of fine soil
Vr = Volume of the sample ring (ml)
Wf = Weight of air-dried fine soil (g)

Thus, the organic carbon storage in soil can generally be calculated based on the fixed depth approach, as shown in the following equation presented by Ellert & Bettany (1995)

Soil C Stock = T*H x BD x Cs* / (1 - *MFp)* ……(2)

Soil C Stock (Soil C stockdepth), in ton/ha
TH = Thickness of each soil layer (cm)
Cs = Soil carbon content (%)
MFp = Moisture factor of fine powder soil
BD = Bulk density (g/cm^3)

Data Analysis

The laboratory data were subjected to statistical analysis using one-way analysis of variance (ANOVA) at a 5% significance level. When significant differences were detected, Fisher's Least Significant Difference (LSD) test was employed to identify specific differences among the treatments, including main effects of Factor A and Factor B, as well as their interaction.

Subsequently, correlation analyses were performed to examine the relationships between carbon storage and the following soil parameters: carbon-to-nitrogen (C/N) ratio, cation exchange capacity (CEC), and the availability of essential nutrients—nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na). These analyses were conducted using Microsoft Excel software.

RESULTS AND DISCUSSION

Soil Organic Carbon, Nitrogen, C/N Ratio and Carbon Sequestration

The variations in soil organic carbon (SOC), total nitrogen content, C/N Ratio and Carbon sequistration content after the application of different doses of palm oil frond biochar, either spread on the soil surface or incorporated into the soil, are presented in Table 1 and Table 2.

Based on Table 1 show that the application of palm oil frond biochar applied on surface and applied to the root zone give the significant total soil N content had increased significantly due to the addition of oil palm frond (OPF) biochar at increased amendment rates.

Table 1. Soil nitrogen total content, C/N Ratio Following the Application of Palm Oil Frond Biochar Applied on the Soil Surface and Incorporated into the Soil

Formulation	Average of total N	BNT 5%	Average of C/N Ratio	BNT 5%
A0B0	0.07	d	28.188	ab
A0B1	0.084	cd	24.602	abc
A1B0	0.124	bc	29.244	a
A1B1	0.156	ab	22.986	bc
A2B0	0.184	a	19.918	c
A2B1	0.186	a	16.975	c

The same lowercase letters following numbers indicate no significant difference according to BNT test at the 5% level

Table 2. Organic carbon and Carbon sequistration Following the Application of Palm Oil Frond Biochar Applied on the Soil Surface and Incorporated into the Soil

Formulation	Organic C(%)	BNT 5%	Carbon Sequistration (tons ha^{-1})	BNT 5%
A0	2.011	b	36.884	b
A1	3.407	a	68,918	a
A2	3,425	a	67.369	a

The same lowercase letters following numbers indicate no significant difference according to BNT test at the 5% level

Treatments with the highest rate (A2B0 and A2B1) had the highest total-N content (0.184% and 0.186% total-N, respectively) and were not significantly different from each other but were different from the control (A0B0) which was only 0.07% total-N. This increase in total N could also support previous ideas on the background that biochar plays a role to improve the soil water and nutrient holding capacity. The characteristics of porosity of biochar enable it to adsorb and hold nitrogen in the soil, which in turn may decrease its risk of leaching or volatilization (Chen *et al*, 2025) . Thus, in addition to enhancing the carbon content of the soil, biochar serves as a soil amendment furnishing improves nutrient use efficiency, which is a necessary aspect of responsible plantation management practices (Septyani *et al*, 2022). This increase in total N indicates that utilizing oil palm frond waste processed into biochar can convert a waste product into a valuable input for improving soil fertility. This is consistent with the objective of mitigating land degradation, as degraded soils often have low organic matter and nutrient content (Herlambang *et al*, 2021).

Table 1 show that biochar application significantly decreased the soil C/N ratio. The most drastic reduction occurred in the highest-rate treatments (A2B0 and A2B1), which had the lowest C/N ratios (19.918 and 16.975). The C/N ratio is a critical indicator of nitrogen availability for soil microorganisms during the decomposition of organic matter. A high C/N ratio indicates that the organic material is nitrogen-poor. This will prompt microbes to draw nitrogen from the soil to meet their needs, a process that causes N immobilization (where nitrogen is bound by microbes and becomes unavailable to plants). This immobilization process can be detrimental to plants. A lower C/N ratio suggests that nitrogen is more available to plants, supporting organic matter decomposition and ultimately enhancing overall soil quality (Van der Sloot *et al*, 2022). This result reinforces the potential of biochar not only as a carbon sequestration agent but also as an effective soil amendment for restoring unsustainable plantation lands. No consistent significant difference was found between the surface application method (B0) and soil incorporation (B1) for the parameters of total N and C/N ratio at the same application rate. For instance, at the highest rate, both A2B0 and A2B1 treatments yielded the highest total N and the lowest C/N ratio. This may indicate that, within the observation period, the benefits of biochar application can be realized regardless of the placement method, possibly due to biotic activity and soil physical processes that help integrate the surface-applied biochar into the upper soil layer.

Table 2 show that biochar application significantly increased the percentage of soil organic C and the total sequestered carbon compared to the control treatment (A0) without biochar. The soil organic C content increased from 2.011% in the control to over 3.4% in the biochar-treated plots. This increase directly impacted the total soil carbon stock, which surged from 36.884 tons ha^{-1} in the control plots to an average of 68.1 tons ha^{-1} in the treated plots. Oil palm frond biochar is a stable, carbon-rich material capable of substantially increasing soil carbon stocks. The pyrolysis process transforms the oil palm frond biomass which would otherwise release its carbon back into the atmosphere into a form of carbon that is highly resistant to decomposition (Safarian, 2023). This addition of stable carbon to the soil is a tangible manifestation of carbon sequestration, whereby carbon that would have become CO_2 emissions is now securely stored in the soil for a very long term.

Another important aspect is the lack of a significant difference between the A1 (3.407% Organic C; 68.918 tons ha^{-1}) and A2 (3.425% Organic C; 67.369 tons ha^{-1}) application rates. Although both rates were significantly superior to the control, increasing the rate from A1 to A2 did not yield a statistically significant increase in carbon storage. The lower application rate (A1) may already be optimal for achieving a substantial increase in carbon stock. From a practical and economic perspective, this finding is highly valuable, as it suggests that farmers or plantation managers could achieve significant carbon sequestration benefits without necessarily using the highest application rate, thus making the practice more cost-effective.

Cation Exchange Capasity and Exchangable Ca, Mg, K, Na

Variations in Cation Exchange Capacity (CEC) and exchangeable cations (Ca, Mg, K, and Na).content after the application of different doses of palm oil frond biochar, either spread on the soil surface or incorporated into the soil, are presented in Table 3 and Table 4.

Table 3 representated that biochar application significantly increased the soil Cation Exchange Capacity (CEC) compared to the control (A0). The CEC value from 5.485 cmol$_c$ kg^{-1} in the control to over 6.9 cmol$_c$ kg^{-1} in the biochar-treated plots. This increase in Cation Exchange Capacity (CEC) is attributed to the intrinsic properties of biochar itself. The physical structure of biochar, formed during its creation process, is characterized by an extremely high surface area. This is because it contains a complex, sponge-like network of countless microscopic pores and channels (Tiwari *et al*, 2022). This intricate structure provides two major benefits when added to soil. First, the tiny pores act like miniature reservoirs, holding water through capillary action. This dramatically increases the soil's overall water retention capacity, making it more resistant to drought. Second, this same porous network provides physical sites where essential plant nutrients can be sheltered and protected from being easily washed away (leached) by rain or irrigation. Chemically, the pyrolysis process creates an abundance of negatively charged functional groups (such as carboxyl and hydroxyl) across this surface. These negative charges function as nutrient magnets, electrostatically attracting and retaining positively charged cations (Nasrollahpour *et al*, 2025).

Table 3. Soil Cation Exchange Capacity (cmol$_c$ kg^{-1}) with Palm Oil Frond Biochar: Surface Application vs. Soil Incorporation

Combination	B0	B1	Average
A0	5.538	5.328	5.485 b
A1	6.792	7.632	7.129 a
A2	6.404	7.516	6.913 a
Average	6.246 b	6.772 a	

The same lowercase letters following numbers indicate no significant difference according to BNT test at the 5% level

Table 4. S oil Exchangable (Ca, Mg, K, Na) with Palm Oil Frond Biochar : Surface vs Incorporated into the Soil

Formulation	Exchangable Ca	Exchangable Mg	Exchangable K	Exchangable Na
	cmol$_c$ kg^{-1}			
A0B0	0.090 d	0.150 d	0.030 c	0.164 d
A0B1	0.096 d	0.148 d	0.036 c	0.150 d
A1B0	0.368 ab	0.412 c	0.312 bc	2.336 ab
A1B1	0.282 c	0.256 b	0.518 a	1.680 c
A2B0	0.400 a	0.578 a	0.374 b	2.510 a
A2B1	0.310 bc	0.538 a	0.576 a	2.316 ab

The same lowercase letters following numbers indicate no significant difference according to BNT test at the 5% level.

This includes essential plant nutrients like calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}), as well as ammonium (NH_4^{+}). By binding these vital nutrients, biochar prevents them from being washed away, or leached, from the root zone, which significantly improves the soil's ability to store and supply nutrients to plants. (Ngo *et al*, 2023). Furthermore, the soil incorporation of biochar (B1) resulted in a significantly higher CEC (6.772 cmol$_c$ kg^{-1}) than surface application (B0) (6.246 cmol$_c$ kg^{-1}). This indicates that the intimate contact between biochar and the soil matrix, achieved through incorporation, is more effective in enhancing the overall soil CEC. This enhancement of CEC also logically explains the previous finding regarding the increase in Total N, as a higher cation adsorption capacity helps retain nutrients such as ammonium (NH_4^{+}), preventing its loss from the root zone (Alkharabsheh *et al*, 2021).

Table 4 showed a significant increase in the content of exchangeable base cations (Ca, Mg, K) across all biochar treatments. The A2B0 treatment exhibited the highest Ca content, while the highest Mg content was achieved in both A2 treatments (B0 and B1), signifying a substantial improvement in soil fertility. The increase in K content was also highly significant, with the highest values recorded in the treatments where biochar was incorporated (A1B1 and A2B1). This suggests that for a nutrient like potassium, the soil incorporation method is superior, possibly because it protects the biochar from surface erosion and accelerates its interaction with the soil's adsorption complex (Septyani, *et al* 2019).

As an effective carbon sequestration agent, biochar adds stable, carbon-rich material to the soil, with studies showing it can nearly double the soil's carbon stock. This is because the pyrolysis process transforms biomass into a form of carbon that is highly resistant to decomposition, locking it away for the long term. Simultaneously, biochar proves to be a potent soil ameliorant (Maulana *et al*, 2025). Its effectiveness comes from fundamentally improving soil chemical properties in two main ways. First, it significantly increases the Cation Exchange Capacity (CEC) due to its high surface area and abundance of negatively charged functional groups, such as carboxyl and hydroxyl. These sites act as magnets, attracting and retaining essential base cations. Second, it enriches the soil with these very cations, including Calcium (Ca), Magnesium (Mg), and Potassium (K), directly boosting fertility (Domingues *et al*, 2020). This dual improvementlocking away carbon while enhancing the soil's structure and nutrient-holding capacity not only contributes directly to the mitigation of land degradation but also supports a more productive and sustainable agricultural system by improving overall soil health and nutrient efficiency.

Interaction Between Carbon Sequistration and Cation exchange capacity

Figure 1 illustrates the relationship between soil Cation Exchange Capacity (CEC) and the amount of sequestered carbon (tons ha^{-1}). Visually, the data indicate a strong and significant positive correlation between these two variables. An increase in CEC, driven in this study's context by biochar application, creates more negatively charged sites on the surfaces of soil colloids and the biochar particles themselves. Interaction between carbon sequistration and Cation exchange capacity showed on Figure 1.

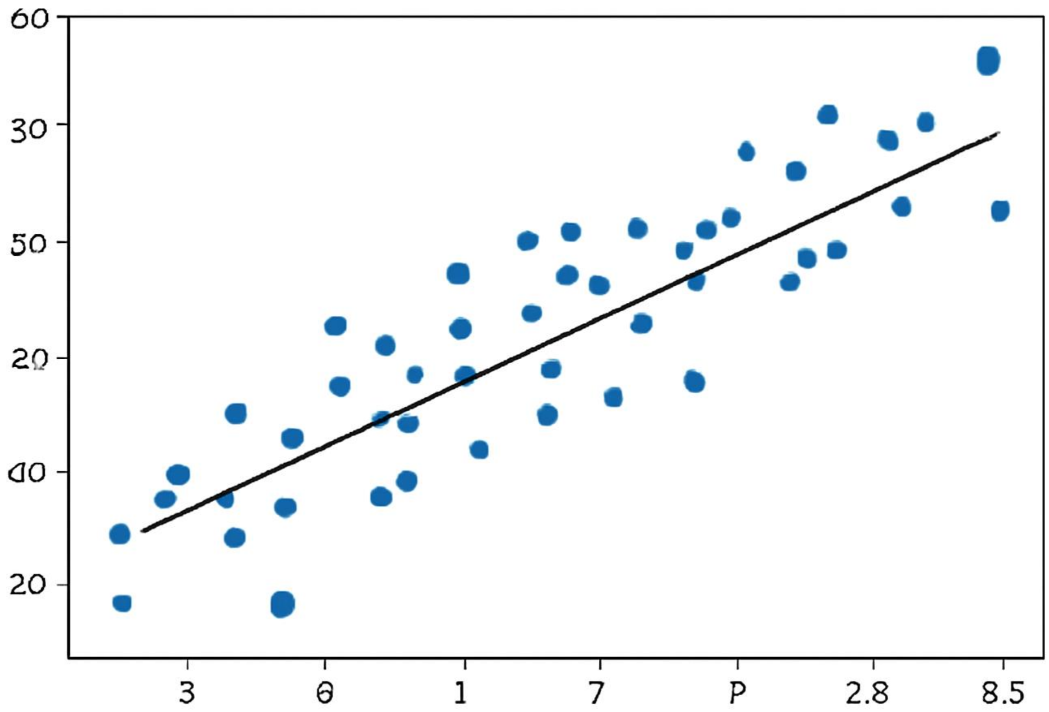

Figure 1. Interaction between soil carbon sequistration (ton.Ha-1) and cation exchange capacity (cmol.kg-1)

These negative sites are not only vital for retaining essential nutrients such as Ca^{2+}, Mg^{2+}, and K^{+}, but they also play a crucial role in the stabilization of soil organic matter (SOM) (Yang *et al*, 2024). Through the cation bridging mechanism, organic molecules, which are the primary constituents of soil carbon, can bind to the surfaces of clay minerals or biochar particles via polyvalent cation intermediaries (Zibo Xu *et al*, 2024). This bonding physically protects the organic carbon from microbial decomposition, thereby extending its residence time in the soil. In other words, soils with higher CEC have a greater capacity to protect and stabilize carbon, thus enhancing the long-term efficiency of carbon sequestration (Li *et al*, 2023).

This correlation implies that carbon sequestration strategies are significantly more effective when implemented concurrently with efforts to increase CEC. This ensures that the carbon captured from the atmosphere and stored in the form of biochar remains stable within the soil and is not easily returned to the atmosphere as CO_2 (Shoudho *et al*, 2024). By increasing both CEC and carbon stocks, biochar not only improves soil chemical fertility but also restores overall soil health, making it an effective solution for rehabilitating critical lands within oil palm plantation areas.

CONCLUSION

Based on discussion , it can be concluded that the application of oil palm frond biochar is a highly effective strategy for CO_2 mitigation and the remediation of degraded land. Biochar significantly increases soil carbon stocks. Application of biochar on the surface and incorporation into soil have the same efect to increase soil carbon sequistration. Biochar fundamentally improves soil fertility by increasing the Cation Exchange Capacity (CEC), total N, essential base cations (Ca, Mg, K) while lowering the C/N ratio to a more ideal level. The method of incorporating biochar into the soil proved superior for enhancing CEC, making it the recommended practice.

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AUTHORS CONTRIBUTIONS

IAPS and LFZ considered and planned the experiment. IAPS carried out the formulation of biochar and level of biochar on oil palm soil. LFZ collected data and also performed analysis data. IAPS interpreting the data AND prepared the manuscript. The authors provided responses and comments on the research flow, data analysis, and interpretation as well as the shape of the manuscript. All the authors have read and approved the final manuscript.

CONFLICT OF INTEREST

"The authors declare no conflict of interest."

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