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Impact of using Boiler Ash as Soil Ameliorant and Nitrogen Fertilizer on CO_2 Emission in Oil Palm Plantations on Peat Soil

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ABSTRACT

Peat soil has an important role in water and carbon storage. However, the utilization of peatland as an agricultural field requires drainage of water and the application of fertilizer or soil ameliorants to increase peat soil's fertility; this will increase greenhouse gas emissions, particularly CO_2, so the function of peat as a carbon sink turns into a source of greenhouse gas emissions. The research aims to determine the effect of using boiler ash as a soil ameliorant and nitrogen fertilizer on CO_2 emission and FFB yield in oil palm plantations on peat soil. The treatment consisted of three levels of boiler ash (0-ton/ha/yr, 1.5-ton/ha/yr and 3-ton/ha/yr) and three levels of nitrogen fertilizer (0 kg N/palm/yr, 0.45 kg N/palm/yr and 0.9 kg/palm/yr). CO_2 emission was measured using the closed chamber method. A PVC pipe with a length of 80 cm is the chamber. 60 cm of pipe was buried in the soil, and the other 20 cm was on the soil surface to catch CO_2 released into the air. The application of a high rate of N fertilizer significantly increased CO_2 emission from 0.56 g/m^2/hour to 0.67 gr/m^2/hour. Applying boiler ash at a low rate reduces CO_2 emission from 0.63 g/m^2/hour to 0.58 g/m^2/hour. The application of boiler ash as a soil ameliorant not only has an impact on CO_2 emissions but also improves peat soil chemical properties by significantly increasing soil pH, total phosphate, available phosphate, and exchangeable Calcium. The high boiler ash and low nitrogen fertilizer rates produce 29.13 t FFB/ha/yr with a CO_2 emission of 0.63 g/m^2/hour.

Keywords: Boiler ash, CO_2 emission, oil palm, peat

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INTRODUCTION

Tropical peat ecosystems have an ecological function, such as storing large amounts of carbon. However, peat ecosystems that are converted into agricultural and plantation areas result in increased greenhouse gas emissions and cause the peat ecosystem to change its function from storing carbon to

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being a source of carbon emissions (Astiani et al., 2022; Pratiwi & Yuwati, 2022). The increase in total greenhouse gas emissions has increased in the 2010–2019 period, and cumulatively, there has been an increase in CO_2 emissions since 1850 (IPCC, 2022). In the 2010–2019 decade, the average greenhouse gas emission reached 59 ± 6.6 $GtCO_2$/yr. It was much higher compared to the previous decade. However, the growth rate between 2010 and 2019 was still lower than between 2000 and 2009. In 2019, around 34% of total GHG emissions, equivalent to 20 $GtCO_2$, came from the energy supply sector. The agricultural, burning, and other land use sectors contribute 22% of the total GHG emissions or 13 $GtCO_2$.

Peat swamp forest is a carbon-rich reservoir with 50–350 Gt stored carbon. However, peat swamp forests can become a source of carbon emissions, contributing to climate change (Lestari et al., 2022). Peat swamp forests release ~0.14 Gt of carbon into the atmosphere annually, equivalent to 1% of fossil fuel emissions (Loisel et al., 2021). Conversion of peatlands into agricultural and plantation areas requires changes in groundwater levels. A decrease in groundwater levels in peatlands will contribute significantly to increased carbon emissions caused by increased mineralization of organic matter and the risk of fire in the dry season (Taufik et al., 2020). It is different in the natural conditions of peat, where the decomposition of organic matter is inhibited by anaerobic conditions (Vernimmen et al., 2020).

The construction of drainage canals will cause a drastic decrease in the water level due to changes in the water level, which will eventually cause organic matter to decompose more easily and produce CO_2 emissions (Hayati et al., 2022). Conversion of tropical peat swamp forests into drainage-based agricultural areas can change greenhouse gas production (Cooper et al., 2020). Although the loss of carbon in peat soils caused by the decomposition of peatlands can be compensated for by plant growth, the conditions for plants in peat areas often tend to have low growth due to low nutrients in peat soils (Ojanen et al., 2019).

The fertility level of peat depends on the level of decomposition, the type of mineral layer beneath the organic layer and the depth of the peat itself (Permatasari et al., 2021). The environmental conditions of the peat, such as waterlogging, high acidity and oxygen deficiency, also worsen the fertility of peat soils, where many micro-nutrients become unavailable to plants (Sutarno & Mohamad, 2022). The low natural fertility of peat soil makes the oil palm plantation industry operate on peat-applied fertilizer in large quantities (Lestari et al., 2022).

Peat soil has a relatively high nutrient content even though it is unavailable to plants (Hartatik et al., 2011); nitrogen fertilization remains important for cultivating oil palm plants in peat soil. However, Long-term use of fertilizer on peatlands, especially on oil palm plantations, will increase the rate of peat soil decomposition and increase net soil CO_2 emissions by 0.85 g/m^2/hour or equivalent to 74.68-ton/ha/year at the immature location and 0.78 g/m^2/hour or the equivalent of 68.38-ton/ha/year at the mature palm location (Stephanie et al., 2021). Meanwhile, the use of ameliorants to improve the chemical properties of peat soil has been widely studied. Amelioration has many benefits in improving the chemical properties of peat soil. The application of mineral soil as an ameliorant in peat soils can slow down the rate of decomposition of peat soils and reduce the rate of CO_2 emissions (Suratman et al., 2013).

This study aims to obtain accurate information regarding using nitrogen fertilizer doses and soil ameliorants to obtain high oil palm productivity and not give high CO_2 emissions to achieve sustainable plantation practices. This study used boiler ash from a palm oil mill as a soil ameliorant. Boiler ash has a pH > 12, which can reduce the negative effect of phenolic acids in peat soils (Ichriani et al., 2021)

MATERIALS AND METHODS

Research Sites

The study was conducted in Rokan Hilir District, Riau Province, Indonesia. In reference to USDA soil classification, the study site is classified into the soil group Typic Haplohemist. Based on Malaysian soil taxonomy, the site is classified as part of the Gondang series (Paramananthan, 2020). These soils have a high water table before being drained, and hemic materials make up the dominant material in the subsurface tier 950–100 cm depth). According to the Schmidt-Ferguson classification, this area has a flat topography with a slope of 0%–4%, annual rainfall of 2,182 mm, and a wet type B climate. The geological study area is a swamp deposit of sand, silt, clay mud and peat.

The research area is an oil palm plantation that has been managed since 1995. In 2013, it underwent replanting, so it is now an oil palm plantation that has undergone its second planting cycle. The research location has an area of 3 Ha. The boiler ash used in this research came from a palm oil mill at the research location. Tables 1 and 2 show the chemical properties of peat soil and boiler ash.

Table 1
Peat soil chemical properties

Parameter	Soil Peat Chemical Properties
pH	3.39
C-organic (%)	23.51
Total-N (%)	1.16
Total-P (ppm)	1,917.16
Available-P (ppm)	133.91
Exch-K (me/100g)	2.85
Exch-Ca (me/100g)	7.66
Exch-Mg (me/100g)	6.50
Exch-Na (me/100g)	0.08
CEC (me/100g)	90.50

Table 2
Boiler ash chemical properties

Parameter	Boiler Ash Chemical Properties
pH	10.95
C-organic (%)	5.61
Total-N (%)	0.02
Total-P (ppm)	3,339.12
Available-P (ppm)	119.28
K (%)	1.35
Ca (%)	2.32
Mg (%)	0.39
Si (%)	76.01
Fe (%)	19.10

Experimental Detail and Sampling

Experimental Design

The study was conducted using a factorial randomized block design with two factors: boiler ash (B) as soil ameliorant with three levels (0, 1.5-ton/ha/yr and 3-ton/ha/yr). The second factor is nitrogen fertilizer (F) with 3 levels (0, 0.45 kg N/palm/yr, and 0.9 kg N/palm/yr) with three replications. Each plot consisted of 16 oil palms, where four were used as sampling points and 12 were used as guard palms. Statistix software version 9.0 was used to generate experimental design, statistical analysis and regression model.

Boiler ash and nitrogen fertilizer are applied in palm circles and areas between palms, spreading evenly over the soil surface. The application of nitrogen fertilizer is carried out one week after the application of boiler ash to prevent the loss of nitrogen nutrients through volatilization due to the increase in soil pH after the application of boiler ash.

FFB Yield Recording

Yield data recording was conducted in one year to ensure the treatment did not affect the yield data starting one year after the first treatment application. Yield recording was carried out every harvesting round (9–10 days). Every bunch from the recorded palm was weighed, and the bunch number was used to calculate the FFB yield. This experiment was conducted on an oil palm field during the planting year 2013.

CO_2 Emission Measurement and Soil Sampling

Measurement of CO_2 emission in all plots uses closed chamber methods. Measurement will be carried out daily from 8 a.m. to 11 a.m. The measurement was conducted within 2 months after the first application of each treatment. An 80 cm pipe of PVC was used as the chamber. 60 cm of pipe was buried in the soil, and 20 cm was kept above the soil surface to catch the CO_2 released into the air. A portable Infrared CO_2 analyzer with the brand BIOEVOPEAK model CO_2A-3010E was used to measure the CO_2 emission.

The formula published by Sano et al. (2010) is used as a reference to calculate CO_2 emissions from peat soil.

$$F = \frac{V}{A} \times \frac{1}{22.4 \times \frac{273.15 + T}{273.15} \times 10^{-3}} \times \frac{dc}{dt}$$

With the symbol notation:

F = Emission CO_2 (μmol/m^2/s)

V = Volume of chamber (m^3)

22.4 = molar volume of gas at standard temperature and pressure that is 22.4 liters/mol or 0.0224 m^3/mole at 0°C (273° K) and 1 atm pressure

T = average temperature in the chamber (^{0}C)

dc/dt = Change in CO_2 concentration over the time (ppm / second)

Soil samples are taken using the disturbed soil method, namely soil samples that are no longer natural and have been disturbed by the external environment. Soil sampling using a soil auger. Soil samples are taken from depths 0–20 cm from the surface. Soil sampling for soil chemical analysis was conducted in the palm circle and interrow. The total number of soil samples from 1 plot is 4 for each location in a palm circle and inter-row. All soil samples are composited to represent each plot.

Water Depth Measurement

Groundwater depth measurements are carried out every time a CO_2 emission measurement is carried out. Groundwater measurements using piezometers were installed at 5 points at the research location. The average value of the measurements is used as groundwater depth data.

RESULTS AND DISCUSSION

The effect of boiler ash and nitrogen fertilizer on the FFB yield and its components is shown in Table 3. Application of boiler ash at rates of 1.5 and 3 tons/ha/yr significantly improved fresh fruit bunches (FFB) production by 28% and 40%, respectively, compared to the control plot. The boiler ash that has been used in this study contains 1.35% K_2O, so the application of boiler ash of 1.5 and 3-ton/ha is equivalent to 33.75 kg MOP/Ha/yr and 67.5 kg MOP/Ha/yr, respectively. The boiler ash content, which contains many macro and micronutrients, is expected to influence plant production and increase the soil's nutrient content and absorption. According to Haron et al. (2008), the utilization of boiler ash as an organic fertilizer, together with decanter cake, provides better nutrient absorption and growth of oil palm seedlings than inorganic fertilizer.

Application of boiler ash significantly increases FFB yield due to an increment in bunch weight. Potassium fertilizer application positively impacts oil palm plants in increasing FFB yields (Prabowo et al., 2023). According to Tohiruddin (2006), the application of KCL with 60% K_2O content increases oil palm FFB production by increasing bunches weight (Tohiruddin, 2006). The result of this study was similar to Arifin et al. (2022), where the application of potassium fertilizer significantly improves FFB yield through increments in a number of bunches. Subandi (2013) states that potassium is a macronutrient essential for the palm. The application of boiler ash, which is rich in potassium, increases the weight of oil palm bunches; this is related to the role of potassium in enzymatic reactions, including carbohydrate and protein metabolism and also increases the quality of seeds and fruit.

Table 3
Main effect of treatment to CO_2 emission, FFB yield and its components on 9 years old oil palm

Treatment		**CO_2 Emission ($g/m^2/hr$)**	**FFB Yield (t/ha/yr)**	**Number of Bunches/ha/yr**	**Average Bunch Weigh (kg)**
Boiler ash (t/ha/yr)	0	0.63 a	16.42 b	1,417.3 a	11.59 b
	1.5	0.58 a	21.02 a	1,484.0 a	14.22 a
	3	0.62 a	23.07 a	1,556.0 a	15.07 a
Nitrogen Fertilizer (kg N/palm/yr)	0	0.56 b	15.46 b	1,157.3 b	13.52 a
	0.45	0.59 ab	23.39 a	1,629.3 a	14.32 a
	0.9	0.67 a	21.65 a	1,670.7 a	13.05 a
CV		16.66	16.08	10.96	13.48

Note: Numbers with the same lowercase letters do not show statistically significant differences in the LSD test at the 5% level

Application of nitrogen fertilizer (Ammonium Sulphate) at a dose of 0.45 kg nitrogen and 0.9 kg nitrogen increased yields by 7.94 tons/ha/year and 6.2 tons/ha/year, respectively, compared to control plots. Nitrogen fertilizer gave different results in increasing yield components compared to boiler ash treatment. Nitrogen fertilizer significantly increases the production of fresh fruit bunches by increasing the number of bunches. However, the application of nitrogen fertilizer did not significantly affect the bunch weight yield components.

The significant increment in the number of bunches per hectare due to the application of nitrogen fertilizers is also consistent with the results of research by Tohiruddin (2006) that the application of nitrogen fertilizers in experiments on oil palm fertilization in the long term in locations with volcanic soil parent material and high average rainfall in North Sumatra significantly increase the production of oil palm plants by increasing the number of bunches per hectare component.

Figure 1 shows the effect of each treatment combination on the value of CO_2 emission. During the CO_2 emission measurement period in April–June 2023, the highest CO_2 emission value is 1.70 g/m^2/hour or the equivalent of 148.92-ton CO_2/ha/year in plots with a combination of high rates of both boiler ash and nitrogen fertilizer. At the same time, the lowest emission value is 0.3 g/m^2/hour, equivalent to 26.28 tons/ha/year in the plot, with a low rate of both boiler ash and nitrogen fertilizer. The emission value in this study is bigger than the results obtained by Batubara et al. (2019), where CO_2 emissions in peat soil with a decomposition level of Saprik peat and a depth of 100–200 cm with 25-year-old oil palm stands can reach 39.3 $\pm$ 2.2-ton CO_2/ha/year. Different results were also reported by Razak (2019) that CO_2 emissions in shallow peat soil with a depth of <175 cm and immature oil palm plantations range from 126.14-ton CO_2/ha/year up to 169.07-ton CO_2/ha/year, where this emission value is much bigger than the results obtained in this study.

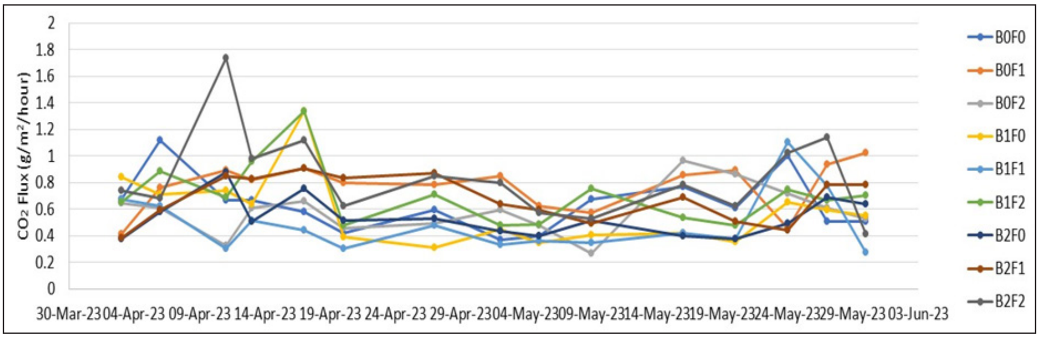

Figure 1. Fluctuation of CO_2 Emission in all plots

The trial was conducted from March to June 2023, which represents the wet season (April 2023 with rainfall > 200 mm) and the dry season (May–June 2023 with rainfall < 150 mm). Monthly rainfall data from January to June 2023 in the study area is presented in Figure 2. It is also to prevent the seasonal effects of climate change (rainfall and temperature) on CO_2 emissions. The effect of climate on CO_2 emission is shown in Figure 1; the CO_2 emission in April 2023 is higher in all treatment plots. Two weeks after treatment, in the last two weeks of April 2023, when the rainfall was still above 200 mm/month, the average value of CO_2 emission was only 0.58 g/m^2/hour. CO_2 emission increased in mid-May 2023 to the average value of 0.64 g/m^2/hour when rainfall dropped to only 101 mm/month. Ray et al. (2020) state that rainfall and soil temperature influence CO_2

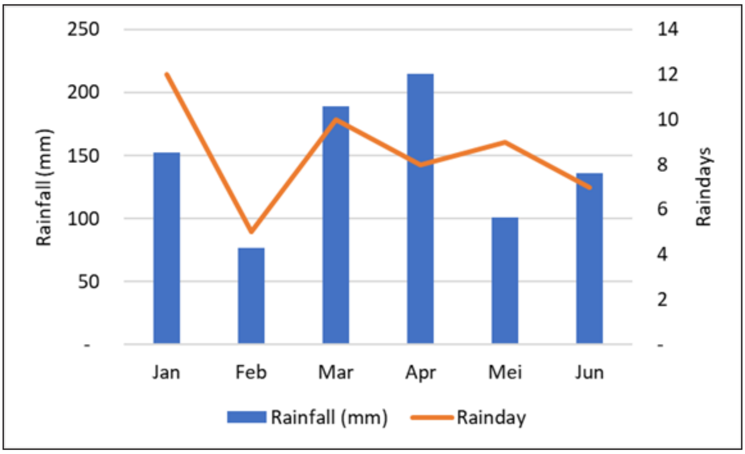

Figure 2. Rainfall distribution Jan–Jun 2023 in Manggala 3 estate (2.5 km from Trial Site)

emissions during the growing season. CO_2 emissions are relatively higher when air and soil temperatures are relatively warmer, and decreased rainfall increases soil temperature and affects groundwater conditions.

Nitrogen fertilizer treatment at a dose of 0.9 kg N/palm/year increased CO_2 emissions by 11% compared to control plots, which was 0.11 g/m^2/hour or equivalent to 9.6 tons CO_2/ha/year. The increase in CO_2 emissions by the application of N fertilizer in this study confirms several previous studies regarding the effect of fertilization on greenhouse gas emissions (Lin et al., 2021; Ojanen et al., 2019).

Nitrogen fertilizer increases CO2 emissions by increasing soil respiration and enzyme performance and the life of soil organisms. According to Babur et al. (2021), nitrogen fertilizer can increase microbial respiration by 97% compared to land that does not receive nitrogen fertilizer application. It is related to the needs of microorganisms for macronutrients such as nitrogen, phosphorus, and sulfur and basic elements such as hydrogen, carbon and oxygen. Nevertheless, according to Fitra et al. (2019) and Razak (2019), CO2 emissions in peat soil are not influenced by the combination of fertilization.

The correlation between CO_2 emissions and environmental conditions is shown in Figure 3. The results showed that the CO_2 emission was directly proportional to the depth of the peat water table. In other words, lowering the peat water level will further increase CO_2 emission on peat soil. These results confirm previous studies that also indicated a linear relationship between the groundwater table and CO_2 emission (Hoyt et al., 2019; Winarna et al., 2017)

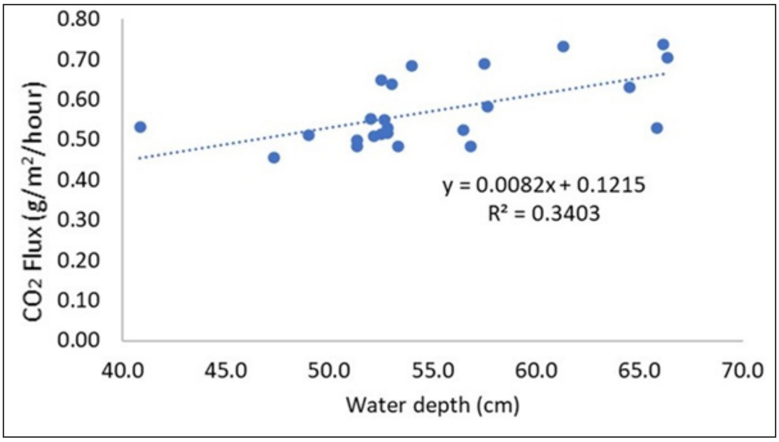

Figure 3. Correlation between CO_2 emissions with water depth (n=24; P-value <0.05)

Soil pH is a standard measurement of the level of acidity or alkalinity in a soil type, which significantly influences soil fertility and the availability of nutrients for plants. Low soil pH values in peat soils are primarily due to organic acids in the soil. Table 4 shows the main effect of each treatment on peat soil chemical properties. Utilization of boiler ash, which has high pH characteristics, increased the pH of the peat soil at the study site by 25% relative to the control plot. This result confirms the previous study by Saputra and Sari (2021) that also reported ameliorants' positive effects on improving soil pH in peat soil.

Table 4
The main effect of treatment on peat soil chemical properties

Chemical Properties	**Boiler ash (t/ha/yr)**			**Nitrogen Fertilizer (kg N/palm/yr)**			**CV**
	0	**1.5**	**3**	**0**	**0.45**	**0.9**	
pH	3.05 b	3.82 a	3.84 a	3.58 a	3.59 a	3.53a	8.12
C-organic (%)	22.25 a	24.73 a	23.26 a	24.36 a	23.45 a	22.43 a	21.92
Total-N (%)	1.16 a	1.18 a	1.17 a	1.18 a	1.15 a	1.18 a	9.44
Total-P (ppm)	3,697 b	4,132 a	4,981 a	4,463 a	4,031 a	4,315 a	49.82
Available-P (ppm)	97.24 b	101.34 ab	130.86 a	111.37 a	110.05 a	108.01 a	29.96
Exch-K (me/100g)	1.80 a	1.96 a	1.98 a	1.914 a	2.09 a	1.73 a	40.78
Exch-Ca (me/100g)	5.40 b	5.98 ab	6.90 a	5.46 b	6.12 ab	6.71 a	18.92
Exch-Mg (me/100g)	3.88 a	2.74 a	3.28 a	2.97 a	2.88 a	4.05 a	42.18
Exch-Na (me/100g)	0.050 a	0.058 a	0.057 a	0.060 a	0.058 ab	0.047 b	23.32
CEC (me/100g)	94.36 a	91.24 a	110.42 a	94.13 a	98.84 a	103.06 a	23.05

Note: Numbers with the same lowercase letters do not show statistically significant differences in the LSD test at the 5% level

The increment of soil pH due to the addition of ameliorants causes a change in the nutrient content available to plants. Total soil P value increased by 34.73%, while available P increased by 34.02% respectively in plots with a high rate of boiler ash relative to the control plot. Furthermore, nitrogen fertilizer treatment did not significantly improve peat soil's chemical properties. The application of nitrogen fertilizers only significantly increased the exchangeable Ca cations and also significantly decreased the content of exchangeable Na cations. Furthermore, applying nitrogen fertilizers and boiler ash tends to increase the soil's cation exchange capacity. Ameliorants are not intended as the main source of nutrients for peat soils. However, the main function of ameliorants is to improve the chemical and biological properties of soil, which is the main aim of using ameliorants. Increasing soil pH will increase the nutrient content available to plants and increase soil microbiological activity.

Table 5 shows several treatment combinations tested in this study. The control plot only produced 12.47-ton FFB/ha/yr with a total CO_2 emission of 0.52 g/m^2/hour. The addition of 0.45 kg N not only improved plant nutrient status but also increased FFB production by 6.15 tons and increased CO_2 emissions by 0.18 g/m^2/hour. The combination of boiler ash and nitrogen fertilizer treatment with doses of 1.5-ton and 0.45 kg N per year, respectively, gives the lowest emission value, viz only 0.45 g/m^2/hour; however, this combination still increases FFB production by 3.82-ton FFB /year. Maximum FFB production was obtained with 3-ton boiler ash and 0.45 kg N, which produced 29.13-ton FFB/ha/yr. However, this combination increases CO_2 emission to 0.63 g/m^2/hour compared to the previous combination.

Table 5
Fitted crop data for specific treatment combination

Boiler ash (t/ha/yr)	Nitrogen Fertilizer (kg N/palm/yr)	FFB Yield (t/ha/yr)	CO_2 Emission (g/m^2/hour)	Leaf (% dry matter)				
				N	P	K	Mg	Ca
0	0	12.47	0.52	2.69	0.166	0.92	0.31	0.52
0	0.45	18.62	0.70	2.73	0.167	1.03	0.29	0.50
1.5	0.45	22.44	0.45	2.79	0.169	1.12	0.33	0.53
3	0.45	29.13	0.63	2.79	0.167	1.06	0.30	0.52

Table 5 shows that various treatment combinations have different values for FFB production, CO_2 emissions and leaf nutrient content. For this reason, the determination of the optimum combination is not only based on production value but also considers environmental conservation values, namely the CO_2 emission value, which affects the accumulation of greenhouse gases in the atmosphere.

CONCLUSION

The application of nitrogen fertilizer significantly increases FFB production by increasing the number of bunches as a production component. Meanwhile, the application of boiler ash significantly increases FFB production by increasing bunch weight. The application of nitrogen fertilizer significantly increases CO2 emissions, while the application of boiler ash does not significantly increase CO_2 emissions. The environmental factor that influences the value of CO_2 emissions is the height of the water level, where the deeper the water level, the more CO_2 emissions will increase and vice versa.

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REFERENCE

Astiani, D., Widiastuti, T., Ekamawanti, H. A., Ekyastuti, W., Roslinda, E., & Mujiman (2022). The partial contribution of CO_2-emission losses from subsidence in small-holder oil palm plantation on a tropical peatland in West Kalimantan, Indonesia. *Biodiversitas*, *23*(12), 6539–6545. https://doi.org/10.13057/biodiv/d231252

Arifin, I., Hanafi, M. M., Roslan, I., Ubaydah, M. U., Karim, Y. A., Tui, L. C., & Hamzah, S. (2022). Responses of irrigated oil palm to nitrogen, phosphorus and potassium fertilizers on clayey soil. *Agricultural Water Management*, *274*, 107922. https://doi.org/10.1016/j.agwat.2022.107922

Babur, E., Uslu, Ö. S., Battaglia, M. L., Mumtaz, M. Z., Fahad, S., Diatta, A. A., Datta, R., & Ozlu, E. (2021). Nitrogen fertilizer effects on microbial respiration, microbial biomass, and carbon sequestration in a mediterranean grassland ecosystem. *International Journal of Environmental Research, 15(4), 655-665.* https://doi.org/10.1007/s41742-021-00336-y

Batubara, S. F., Agus, F., Rauf, A., & Elfiati, D. (2019). Impact of soil collar insertion depth on microbial respiration measurements from tropical peat under an oil palm plantation. *Mires and Peat*, *24,* Article 06. https://doi.org/10.19189/MaP.2018.DW.373

Cooper, H. V., Evers, S., Aplin, P., Crout, N., Dahalan, M. P. B., & Sjogersten, S. (2020). Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. *Nature communications*, *11*(1), Article 407. https://doi.org/10.1038/s41467-020-14298-w

Fitra, S. J., Prijono, S., & Maswar, M. (2019). The effect of fertilization of peat land on soil characteristics, CO_2 emissions, and productivity of rubber plant. *Jurnal Tanah dan Sumberdaya Lahan, 6*(1), 1145-1156. https://doi.org/10.21776/ub.jtsl.2019.006.1.13

Hayati, N., Sari, N., Arief, R., & Uzzulfa, M. A. (2022). Parameters to estimate CO_2 emission in peatland area based on carbon content and subsidence rate from SAR interferometry. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *43*(B3-2022), 277–284. https://doi.org/10.5194/isprs-archives-XLIII-B3-2022-277-2022

Haron, K., Mohammed, A. T., Halim, R. M., & Din, A. K. (2008). *Palm-Based Bio-Fertilizer from Decanter Cake and Boiler Ash of Palm Oil Mill*. Malaysian Palm Oil Board (MPOB).

Hartatik, W., Subiksa, I. G. M., & Dariah, A. (2011). *Sifat Kimia dan Fisik Tanah Gambut. Pada: Pengelolaan Lahan Gambut Berkelanjutan* [Chemical and Physical Properties on Peat Soil. In: Sustainable Peat Soil Management] Balai Penelitian Tanah.

Hoyt, A. M., Gandois, L., Eri, J., Kai, F. M., Harvey, C. F., & Cobb, A. R. (2019). CO2 emissions from an undrained tropical peatland: Interacting influences of temperature, shading and water table depth. *Global Change Biology*, *25*(9), 2885-2899. https://doi.org/10.1111/gcb.14702

Ichriani, G. I., Sulistiyanto, Y., & Chotimah, H. E. N. C. (2021). The use of ash and biochar derived oil palm bunch and coal fly ash for improvement of nutrient availability in peat soil of Central Kalimantan. *Journal of Degraded and Mining Lands Management*, *8*(3), 2703. https://doi.org/10.15243/jdmlm. 2021.083.2703

IPCC. (2022). *Climate Change 2022 Mitigation of Climate Change - Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change.

Lestari, I., Murdiyarso, D., & Taufik, M. (2022). Rewetting tropical peatlands reduced net greenhouse gas emissions in Riau province, Indonesia. *Forests*, *13*(4), Article 505. https://doi.org/10.3390/f13040505

Lin, S., Zhang, S., Shen, G., Shaaban, M., Ju, W., Cui, Y., Duan, C., & Fang, L. (2021). Effects of inorganic and organic fertilizers on CO_2 and CH_4 fluxes from tea plantation soil. *Elementa*, *9*(1), Article 090. https://doi.org/10.1525/elementa.2021.090

Loisel, J., Gallego-Sala, A. V., Amesbury, M. J., Magnan, G., Anshari, G., Beilman, D. W., Benavides, J. C., Blewett, J., Camill, P., Charman, D. J., Chawchai, S., Hedgpeth, A., Kleinen, T., Korhola, A., Large, D., Mansilla, C. A., Muller, J., Belleh, S. V., West, J. B., … & Wu, J. (2021). Expert assessment of future vulnerability of the global peatland carbon sink. *Nature climate change*, *11*(1), 70-77. https://doi.org/10.1038/s41558-020-00944-0

Ojanen, P., Penttilä, T., Tolvanen, A., Hotanen, J. P., Saarimaa, M., Nousiainen, H., & Minkkinen, K. (2019). Long-term effect of fertilization on the greenhouse gas exchange of low-productive peatland forests. *Forest Ecology and Management*, *432*, 786–798. https://doi.org/10.1016/j.foreco.2018.10.015

Paramananthan, S. (2020). *Organic Soil of Malaysia Standard Series Description*. Param Agricultural Soil Survey.

Pratiwi, D., & Yuwati, T. W. (2022, November). Paludiculture: Peatland utilization to support climate change adaptation. *IOP Conference Series: Earth and Environmental Science*, *1109*(1), Article 012001. https://doi.org/10.1088/1755-1315/1109/1/012001

Permatasari, N. A., Suswati, D., Arief, F. B., Aspan, A. A., & Akhmad, A. (2021). Identifikasi beberapa sifat kimia tanah gambut pada kebun kelapa sawit rakyat di Desa Rasau Jaya II Kabupaten Kubu Raya [Identification of chemical peat soil properties in smallholder oil palm plantation in Rasau Jaya II Village, Kubu Raya district]. *Agritech: Jurnal Fakultas Pertanian Universitas Muhammadiyah Purwokerto*, *23*(2), 199-207. https://doi.org/10.30595/agritech.v23i2.12616

Prabowo, N. E., Foster, H. L., & Nelson, P. N. (2023). Potassium and magnesium uptake and fertiliser use efficiency by oil palm at contrasting sites in Sumatra, Indonesia. *Nutrient Cycling in Agroecosystems*, *126*(2), 263-278. https://doi.org/10.1007/s10705-023-10289-7

Razak, F. R. (2019). *Dampak Pemupukan Tanaman Kelapa Sawit Terhadap Respirasi Heterotrofik di Lahan Gambut* [The Impact of Oil Palm Fertilization on Heterotrophic Respiration in Peat Soil]. Fakultas Pertanian, Universitas Tanjungpura

Ray, R. L., Griffin, R. W., Fares, A., Elhassan, A., Awal, R., Woldesenbet, S., & Risch, E. (2020). Soil CO2 emission in response to organic amendments, temperature, and rainfall. *Scientific Reports*, *10*(1), Article 5849. https://doi.org/10.1038/s41598-020-62267-6

Sutarno, M. S., & Mohamad, H. M. (2023). Peat soil compaction characteristic and physicochemical changes treated with eco-processed pozzolan (EPP). *Civil Engineering Journal (Iran)*, *9*(1), 86–103. https://doi.org/10.28991/CEJ-2023-09-01-07

Saputra, R. A., & Sari, N. N. (2021). Ameliorant engineering to elevate soil pH, growth, and productivity of paddy on peat and tidal land. *IOP Conference Series: Earth and Environmental Science*, *648*(1), Article 012183. https://doi.org/10.1088/1755-1315/648/1/012183

Sano, T., Hirano, T., Liang, N., Hirata, R., & Fujinuma, Y. (2010). Carbon dioxide exchange of a larch forest after a typhoon disturbance. *Forest Ecology and Management*, *260*(12), 2214–2223. https://doi.org/10.1016/j.foreco.2010.09.026

Stephanie, M. C., Gusmayanti, E., & Pramulya, M. (2021). Emisi CO_2 pada perkebunan kelapa sawit di lahan gambut yang telah mengalami pemupukan. [CO2 emission in oil palm plantations on peat soil that have been fertilized]. In *Prosiding Seminar Nasional Penerapan Ilmu Pengetahuan Dan Teknologi : Kampus Merdeka Meningkatkan Kecerdasan Sumberdaya Manusia Melalui Interdispliner Ilmu Pengetahuan Dan Teknologi* (pp. 205-210). Universitas Tanungpura. https://doi.org/10.26418/pipt.2021.8

Suratman, Sukarman & Hariyadi. (2013, Mei 29). Peran amelioran tanah mineral dalam mengendalikan laju emisi CO_2 pada lahan gambut [The role of mineral soil as ameliorant in controlling the rate of CO2 emission in peat soil]. [Paper presentation]. *Prosiding Seminar Nasional Pertanian Ramah Lingkungan*, Bogor, Indonesia.

Subandi, S. (2013). Peran dan pengelolaan hara kalium untuk produksi pangan di Indonesia [The role and management of potassium nutrient for food production in Indonesia]. *Pengembangan Inovasi Pertanian, 6*(1), 1-10.

Taufik, M., Minasny, B., McBratney, A. B., Van Dam, J. C., Jones, P. D., & Van Lanen, H. A. J. (2020). Human-induced changes in Indonesian peatlands increase drought severity. *Environmental Research Letters*, *15*(8), Article 084013. https://doi.org/10.1088/1748-9326/ab96d4

Tohiruddin, L. (2006). Comparison of the response of oil palm fertilisers at different locations in north and south Sumatra. In *International Oil Palm Conference 2006, Nusa Dua, Bali* (pp. 188-200). CiNii.

Vernimmen, R., Hooijer, A., Akmalia, R., Fitranatanegara, N., Mulyadi, D., Yuherdha, A., Andreas, H., & Page, S. (2020). Mapping deep peat carbon stock from a LiDAR based DTM and field measurements, with application to eastern Sumatra. *Carbon Balance and Management*, *15*(1), Article 4. https://doi.org/10.1186/s13021-020-00139-2

Winarna, W., Yusuf, M. A., Rahutomo, S., & Sutarta, E. S. (2017). Impacts of water table and soil ameliorant on soil moisture, CO2 emission, and oil palm yield on peat soil. *Jurnal Penelitian Kelapa Sawit*, *25*(3), 147-160. https://doi.org/10.22302/iopri.jur.jpks.v25i3.32