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THE EFFECTS OF BIOCHAR INCORPORATION ON THE CO_2, N_2O, AND CH_4 EMISSIONS FROM THE SOILS OF STALLHOLDER PALM OIL PLANTATIONS, JAMBI PROVINCE INDONESIA

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Abstract. *The domestic agricultural sector contributes 18% to the national greenhouse gas emissions (GHG); which is higher compared to its global counterpart. Biochar incorporation into the soils shows the potential to reduce soil GHG emissions. The objective of this study was to ascertain how biochar addition affects CO_2, N_2O and CH_4 emissions from the soils of stallholder palm oil plants. Coffee hash was pyrolyzed at 500^0C to prepare biochar, which was then ground to pass a 100-mesh sieve. Three plots (50m x 50 m) consisting of 27 subplots (1 m x 1 m) were used as the experimental design in the field. Biochar was incorporated into the soil subplots of 0, 10, and 20-ton biochar/ha. A static chamber was installed on the soil surface to collect gas generated from the soil on days 0, 5, 10, 20, 40, and 60. All gas collection was conducted at 30 min after the chamber lid installation. The soil CO_2, N_2O, and CH_4 emissions of control soils ranged from 712 to 862, 7.28 to 9.46, and -0.0036 to 0.0014 kg/d/ha, respectively. The incorporation of 10 and 20-ton biochar per hectare decreased the emissions of CO_2 and N_2O up to 16.8% and 33.8%, respectively; whereas an uptake was observed for the CH_4 gas. The CO_2 and N_2O emissions from the 10-ton/ha and 20-ton/ha biochar-incorporated soils differ significantly compared to the control soils, but the CH_4 emissions do not. This result shows that biochar incorporation to the oil palm soils reduces the CO_2 and N_2O emissions, but not CH4 emissions.*
Keywords: *biochar; carbon dioxide; greenhouse gas mitigation; methane; nitrous oxide*

1. Introduction

Agriculture contributes significant emissions of CO_2, CH_4, and N_2O to the atmosphere (Paustian *et al*., 2016). The main sources of carbon dioxide emissions are the decomposition or combustion of soil organic materials and litter as well as soil respiration (Smith *et al*., 2008). Methane gas is formed when organic matter decomposes in environments with limited oxygen, during the fermentation digestion of ruminants, when manure is stored, and when rice is grown in floodplains. When the amount of accessible nitrogen exceeds the amount needed by plants, particularly in moist conditions, nitrous oxide is formed by microbial decomposition of nitrogen in the soil and nitrogen fertilizers. Agricultural activities as a whole contribute to greenhouse gas (GHG) emissions of $6x10^9$ tons of CO_2 equivalent; it is equivalent to 12% of total global GHG emissions (Paustian *et al*., 2016). Between 52% and 84% of the world's anthropogenic CH_4 and N_2O emissions come from agriculture (Smith, 2016). If others land use change such as deforestation, housing, and industrial complex included, the contribution rises to 30% (Cantrell *et*

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al., 2012; Smith, 2016). Although agriculture is a significant contributor to global GHG emissions, it also has a great potential to contribute to GHG emission mitigation (Smith *et al*., 2008; Collier *et al*., 2014; Hassan *et al*., 2022). Numerous agricultural practices, including better agricultural management, restoring degraded land, cultivating organic soils, and adding biochar to agricultural land, have the potential to lower GHG emissions (Shen *et al*., 2017).

Future development of national and international climate policies is more concentrated on reducing GHG emissions in the energy, industry, and transportation sectors and deforestation. However, there is still a lack of attention given to the possibility of reducing GHG emissions from agriculture. At the COP-26 meeting in 2021, Indonesia declared its intention to reduce GHG emissions to net zero emissions by 2060. However, Indonesia produces the majority of the world's non-CO_2 emissions through land use and agriculture (Wang *et al*., 2017). This may relate to Indonesia's oil palm plantations, which cover more than 16 million hectares, and 41% are accounted for by smallholder farmers (Woolf *et al*., 2021). This may imply that smallholder oil palm farmers can contribute to lowering GHG emissions from agriculture.

Recently, biochar, a by-product of biomass pyrolysis, has drawn a lot of interest due to its potential application in reducing climate change caused by agricultural soils (Yoo *et al*., 2015). According to the International Panel on Climate Change (IPCC), one of the negative emission technologies that removes greenhouse gases from the environment is biochar (Smith, 2016). There is a substantial likelihood that incorporating biochar into the soil will be able to lower GHG emissions from the soil, even though there is currently conflicting data on the use of biochar for GHG reduction. Inconsistencies in research results are typically attributed to variations in soil parameters, the source of biochar feeding materials, and pyrolysis settings (Dai *et al*., 2021), pyrolysis conditions (Kotus & Horak, 2021; Collier *et al*., 2014), and research methodology (Hardy *et al*., 2019). As an illustration, biochar amendment to the soil reduces CO_2, N_2O, and CH_4 emissions (Jindo *et al*., 2014), reduces N_2O but increases CH_4 emissions (Collier *et al*., 2014; Kotus & Horak, 2021), increases CH_4 emissions (Dai *et al*., 2021), reduce CO_2 emissions but not significant for N_2O and CH_4 (Hardy *et al*., 2019). Those studies (Collier *et al*., 2014; Jindo *et al*., 2014; Dai *et al*., 2021; Kotus & Horak, 2021) however probably justify that adding biochar to soil of oil palm plantations is a potential strategy for lowering GHG emissions. In this study, it is hypothesized that using a parent material with a high carbon content will improve the properties of the biochar and decrease its efficiency in reducing GHG emissions from soils. Indonesia's stallholder palm oil plantation accounted for 6.56 million hectares or about 41% of total Indonesia's oil palm area in 2016. This study's goal was to ascertain how adding biochar to the soil of stallholder palm oil plantations affected CO_2, N_2O, and CH_4 emissions.

2. Methods

2.1. Field experiments and biochar incorporation

This field research was conducted on stallholder palm oil plantations in Muaro Jambi Regency, Jambi Province. Stallholder palm oil plantations with aged of 5 to10 years were selected as the research site. Three random plots measuring 50m x 50m were established in the oil palm and 9 subplots measuring 1m x 1m at least 5 m apart (Case *et al.*, 2017) were established in each plot. Biochar 10-ton/ha and 20-ton/ha were incorporated into the soils of three subplots, respectively, and the rest 3 subplots were used as the control (no biochar addition). A total of 27 subplots were used in this study. Biochar was incorporated into the top 0-5 cm of soil by mixing it using hands after litter, stone and other interfering objects were removed (Figure 1).

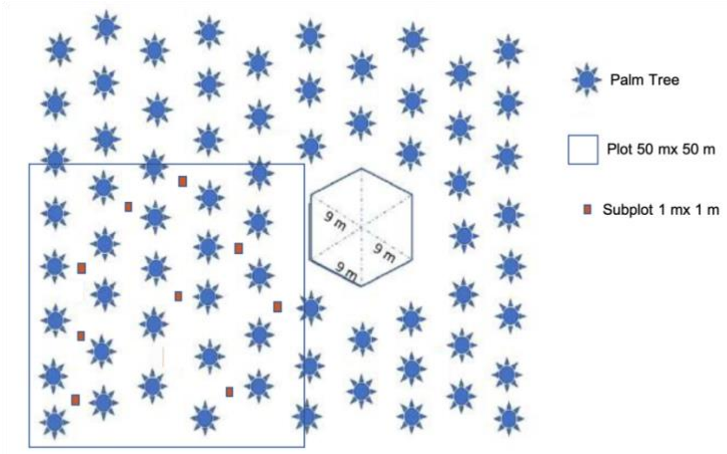

Figure 1. A plot and subplots were randomly established on the stallholder palm oil plantations

2.2. Static chamber installation

After mixing biochar-soil on the subplot was allowed to reach equilibrium for 7 days, a static chamber was installed at the subplot soil surface. The chamber was made up of an anchor that was buried in the ground and a cover that was placed on top of the anchor during gas collecting. To prevent gas leaking, the edge of the anchor was sunk about 5 cm into the ground. The lid was then firmly fastened to the anchor. The gas collection was conducted every 30 min after the lid had been placed securely on the anchor. In this study, the gas samples were collected on days 0, 5, 10, 20, 40, and 60, between 11:00 am and 13:00 pm. A syringe of 50 mL was used to collect the gas from the chamber and the gas was transferred into three 12 mL vacuum vials and transported to the lab in an ice box and stored in a freezer until analysis. Each gas sample in the vial was analysed using Gas Chromatograph with a Thermal Conductivity Detector (TCD) for CO_2 detection and Flame Ionization Detector (FID) for both N_2O and CH_4 gases.

2.3. Data Conversion and Statistical analysis

The CO_2, N_2O, and CH_4 gas concentrations from GC analysis given in part per million (mg/L). By considering the area and volume of the chamber, the concentrations of the gas were then converted into kg/day/hectare. Cumulative concentration is given in kg/hectare after the data gas concentrations are added together during the gas collection.

The averages and standard deviations for CO_2, N_2O, and CH_4 gas emissions were calculated. Different biochar incorporation rates were evaluated for their effects on the measured gas emissions using a one-way analysis of variance.

3. Results and Discussion

3.1. Biochar characterization

Table 1 lists the chemical and physical characteristics of palm shell biochar produced by a segmented chamber reactor (SCR). The chemical and physical properties of the resulting biochar are impacted by variations in the pyrolysis period. The biochar-palm shell ratio, the C content, and the C/N ratio all decreased to offset the increase in pyrolysis duration from 1-4 hr.

This could mean that the selective release of the palm shell constituent atoms during pyrolysis (Oliveira *et al*., 2018) caused a drop in the biochar production, an increase in C content, a C/N ratio, a pH increase, and an increase in the specific surface area of the produced biochar (Table 1).

The selective and disproportionate release of C, H, N, and O atoms (Cantrell *et al*., 2012) alters the atomic structure and rearranges them to produce molecules with high aromaticity and stability. The extra stability of the biochar is obtained from the formation of bonds in the cyclic molecular structure in the flat *p* orbitals (Oliveira *et al*., 2018). Cyclic molecules and high aromaticity contribute to the formation of biochar durability up to 10 – 10,000 times stronger than the original material molecules (Wang *et al*., 2017). Due to the high surface area of biochar as a greenhouse gas absorber, the conversion of biomass into biochar directly reduces GHG emissions. Table 1 also demonstrates that the specific surface area of the biochar generated was unaffected by the duration of pyrolysis (from 1-4 hr). The temperature of the pyrolysis in this study exceeded 500^0C, which is adequate for producing biochar with a wide surface area (Woolf *et al*., 2021). The temperature and the parent materials have an impact on the surface area of the biochar produced (Jindo *et al*., 2014). The pH of the biochar produced by a 1:10 biochar-water ratio was >8.0 (Table 1), demonstrating the presence of oxygen-containing functional groups on the biochar surface (Oliveira *et al*., 2018). Biochar with an alkaline surface has good properties to be applied to mineral soils (acidic soils) so that it can neutralize soil pH.

The carbon contents of palm shell biochar produced using a segmented chamber pyrolysis reactor are in a range of 52.7-54.1%. These figures are comparable to that of biochar from paper fibre deposits mixed with wheat husk, which contains 53.1% carbon (Kotus & Horak, 2021).

3.2. Emissions of CO_2 from the soils

Carbon dioxide emissions from the soil in the three research plot areas without biochar incorporation and measured from the days of 0-60 are in a range of 712±44-862±56 kg CO_2/d/ha (Figure 2A). We observed that the averages of the CO_2 emissions are found slightly higher in plot 3 (790±39) compared to plot 1 (732±26), and 782±23 kg CO_2/d/ha for plot 2. However, the average CO_2 emissions from the three plots were consistently higher than those reported by Kotus and Horak (2021). The amount of CO_2 gas generated from the soil is affected by a number of parameters such as temperature, microbial activity, soil organic content, and soil moisture (Oliveira *et al.*, 2018; Woolf *et al.*, 2021). Therefore, it is expected that the soil of the tropics releases more CO_2 emissions compared to sub-tropical soil (Collier *et al.*, 2014). The field experiment for this study was carried out from August to October 2022 during the rainy season. According to Wachiye *et al.* (2020), the rise in soil moisture during the wet season is followed by the increase in CO_2 emissions from the soil, where CO_2 emissions are typically larger in the wet season than in the dry season. Another study by Deng *et al.* (2017) revealed that the rains predominantly increased soil CO_2 emission through raising soil microbial biomass or altering the composition of microbial communities. Despite the lack of soil temperature measurements in this study, it is believed that temperature effect on CO_2 emission is small as a result of the soil temperature's low annual variation (Wachiye *et al.*, 2020). According to the analysis of variance, there is no discernible difference between the control experiment plots for CO_2 emissions ($p > 0.05$).

Table 1. Chemical and physical parameters of biochar from palm shells (n = 3)

Time pyrolysis (jam)	Biochar (%)	Temperature (^{0}C)*	C %)+	N (%)+	Ratio C/N	pH#	SSA@ (m^2 g^{-1})
1	36 ± 2	500 ± 36	52.3	1.45	36.1	8.3 ± 0,04	170.3
2	35 ± 4	500 ± 32	53.3	1.47	36.2	8.5 ± 0,03	172.3
3	32 ± 4	500 ± 32	52.7	1.47	35.9	8.4 ± 0,04	171.9
4	30 ± 5	500 ± 28	54.1	1.49	37.7	8.5 ± 0,03	162.5

**Temperature measurement with Digital Gun Infrared Temperature Meter*
+ The results of SEM-ADS analysis
#Measured ion biochar-water suspension 1:10 using a pH meter
@Specific Surface Area (SSA) determined by molybdenum blue (MB) method

The incorporation of 10 ton/ha biochar resulted in a decrease in CO_2 emissions between 8.2-9.9% compared to the control soils at days 0, 5, 10, 20, and 40 after the biochar incorporation into the soils. However, at day 60, the CO_2 emissions are about 1% lower than the control soils (Figure 2B). It appears that the CO_2 emissions tend to increase to a level of the control soils when measured at longer time after the biochar application. The incorporation of 20-ton biochar/ha is not followed by a proportional decrease in the CO_2 emission (Figure 2C) but the emissions are about the same level as the 10-ton biochar incorporation (Figure 2B). This may suggest that the reduction in CO_2 emissions from the soil cannot be explained by CO_2 adsorption to the surface of biochar, it is because an increase in biochar incorporation does not necessarily result in a proportionate drop in CO_2 emissions.

One-way analysis of variance showed that there is a significant difference in daily CO_2 emissions from soil oil palm plantations ($p < 0.05$) between the biochar incorporation soils and the control soils; however, there was no significant difference between applying biochar at 10-ton/ha and 20-ton/ha rates. According to Kotus and Horak (2021), a number of variables, including the availability of soil organic matter, the interaction of chemical parameters, the physical and biological processes of the soil, and environmental variables like temperature, humidity, and rainfall, affect the rate of CO_2 emissions from the soil. Increased CO_2 gas emissions may result from the addition of biochar to soils with a high organic content (Dai *et al*., 2021).

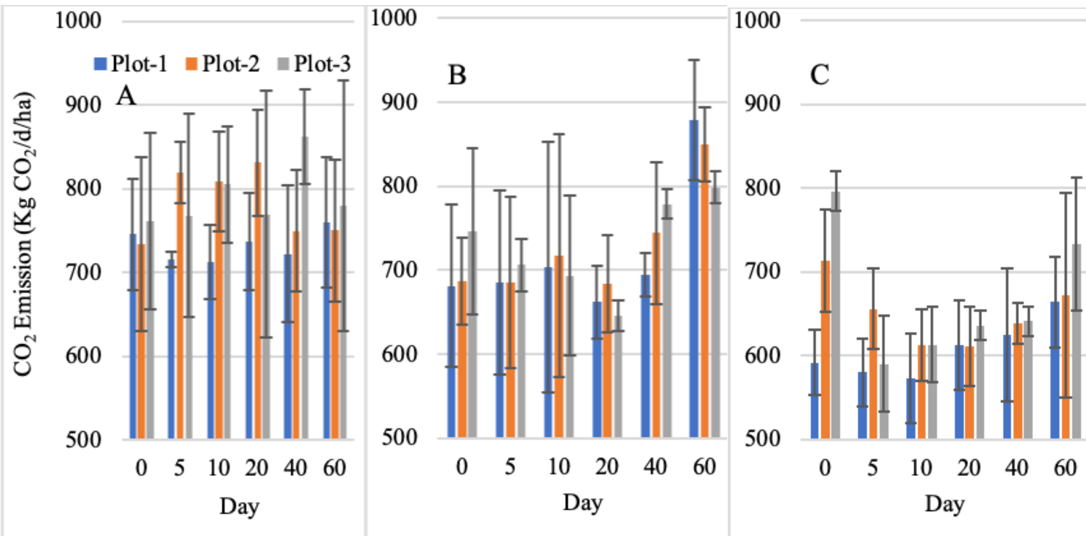

Figure 2. CO_2 gas emissions from (A) the control soils, (B) 10 ton/ha, and (C) 20 ton/ha biochar incorporation. Each bar represents independent three measurements and error bars indicate ±SD

It can be observed (Figure 2B and Figure 2C) that the incorporation of 10-ton/ha and 20-ton/ha biochar reduces CO_2 gas emissions on days 5, 10, 20, and 40 after the incorporation. However, the CO_2 emissions tend to increase at day 60 compared to the control soils. One-way analysis of variance shows a significant difference between the biochar-incorporated soil vs the control for all three experiment plots ($p < 0.05$). It needs to be recognized that variations among gas measurements are common for data collected from environment as indicated by error bar at Figure 2. A number of environmental factors such soils moisture, organic contents, minerals, rainfall and soil microorganism activity at the time of gas was collected may contribute to high variation among measurements (Kotus & Horak, 2021).

3.3. The cumulative CO_2 emissions

The cumulative CO_2 emissions are calculated by the sum of all CO_2 measurements from day 0-60 and expressed in a unit kg/ha (Figure 3). It shows that the incorporation of 10 and 20 ton/ha biochar reduces the cumulative CO_2 emission by 2.0 and 17.0% for plot 1, 7.0 and 17.8% for plot 2, and 7.9 and 15.5% for plot 3, respectively, compared to the control soils. The increase in biochar incorporation of 10-20 ton/ha biochar improves the reduction of CO_2 emissions by 15%. A similar result was also reported by Kotus and Horak (2021) where the incorporation of 10-ton/ha biochar was accompanied by the addition of N fertilizer. According to Case *et al.* (2017), adding biochar to the soil reduced net soil CO_2 equivalent emissions by 37% and average CO_2 emissions by 33%.

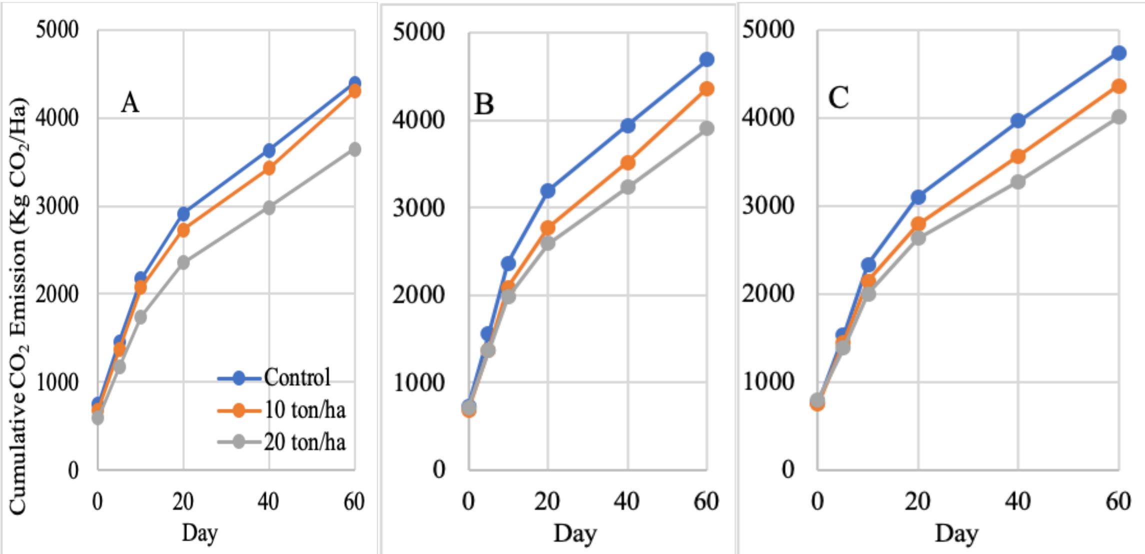

Figure 3. Cumulative CO_2 gas emissions (kg CO_2/ha) from the control and the soils integrated with 10 and 20 tons/ha of biochar

There are a number of scenarios that have been used to explain why adding biochar to the soil might lower CO_2 emissions. Increased soil microbial biomass and "negative priming" of native soil carbon mineralization may both result from complexation of soil organic matter with biochar particles (Case *et al*., 2014; Woolf *et al*., 2021). In alkaline conditions, high pH values of the biochar, and the presence of alkaline metals, CO_2 driven from the soils may precipitate as carbonates on the surface of the biochar, explaining the reduction of soil CO_2 emissions (Case *et al*., 2014). The biochar used in this investigation had high pH values (Table 1), which may have caused a significant amount of precipitation to fall on the biochar surface. It appears that a combination of biotic and abiotic mechanisms may account for the suppression of soil CO_2 emissions in this study (Case *et al*., 2014).

It needs to be emphasized that in addition to the reduction of CO_2 emission due to the biochar incorporation, biochar also increases the soil carbon stock since it is a non-degradable substance, thus does not affect emissions because biochar does not disintegrate (Lavesque *et al.*, 2020). However, about 20% of the carbon present in the biochar parent material can be searched into the soil, considering the rate at which agricultural biomass loses carbon during the production of biochar (Lee *et al.*, 2022).

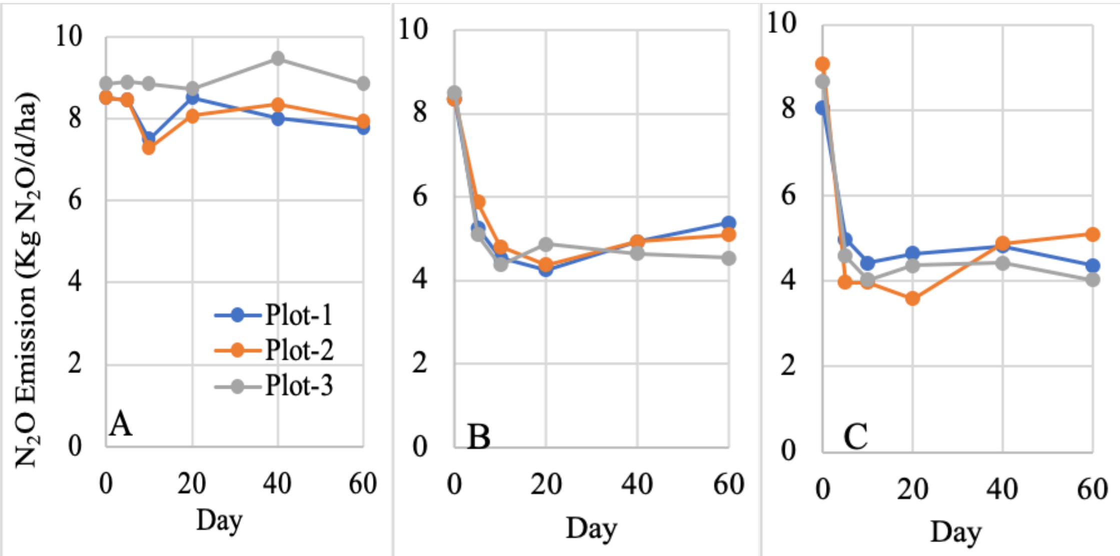

Figure 4. The N_2O gas emissions from the control soils (A), 10 (B) and (c) 20 ton/ha biochar incorporation into soils

3.4. Emission of N_2O from the soil

As can be seen from Figure 4A the N_2O emissions from the control soils are in a range of 7.28±0.48-9.46±0.19 kg N_2O/d/ha. The incorporation of 10 and 20 ton/ha biochar at day 0 decreases by 2.0 and 0.2% of the control soils. The greater reductions of N_2O emissions of 10 and 20 ton/ha biochar incorporation were observed at day 5 (38.5 and 48.8%), day 10 (52.4 and 48.6%), day 20 (53.7 and 54%) and day 40 (45.2 and 40.4%), respectively. However, at day 60 the reduction was only 10.2 and 5.5%. The incorporation of 10 and 20 ton/ha biochar was followed by a significant decrease in N_2O emissions from day 5-40, but it increases on day 60 (Figure 4B and Figure 4C). The research published by Cayuela *et al.* (2019), Chen *et al.* (2020), and Lee *et al.* (2022) provides support for the findings of this study. Because of its ability to buffer acid, biochar is crucial in reducing the release of N_2O gas from the soil as a result of pH variations. Additionally, biochar functions as an "electron shuttle," facilitating electron transport to soil denitrifying bacteria and preventing N_2O from being converted to N_2 (Cayuela *et al.*, 2019). The high capacity of biochar to absorb nutrients lowers the availability of N minerals, which lowers the rate of N_2O emission reduction (Chen *et al.*, 2020). Higher available N concentrations for nitrification or denitrification processes may have contributed to higher N_2O emissions on day 60 for the biochar incorporation of 10 and 20 ton/ha.

Biochar with a high C/N ratio could stabilize N in the soil and caused a low N_2O emission (Lee *et al*., 2022). The biochar used in this study has a C/N ratio in the 35.9–37.7% range, which is 51.8%–61.6% greater than biochar made from barley straw and 54.1–63.4% higher than biochar made from poultry manure (Lee *et al*., 2022). Nitrous oxide gas emissions from the soils of oil palm plantations incorporated with 10-ton/ha and 20-ton/ha biochar were considerably lower than the control soils ($p< 0.05$). However, there was no difference between incorporated with 10 and 20 tons of biochar toward N_2O emission from the soils ($p > 0.05$).

A cumulative emission of N_2O gas as given in Figure 5 shows a decrease of 33.18% on average vs the control soils. However, a study reported that N_2O emission reduction could be up to 80% when biochar and lime were incorporated into the soil (Hassan *et al*., 2022).

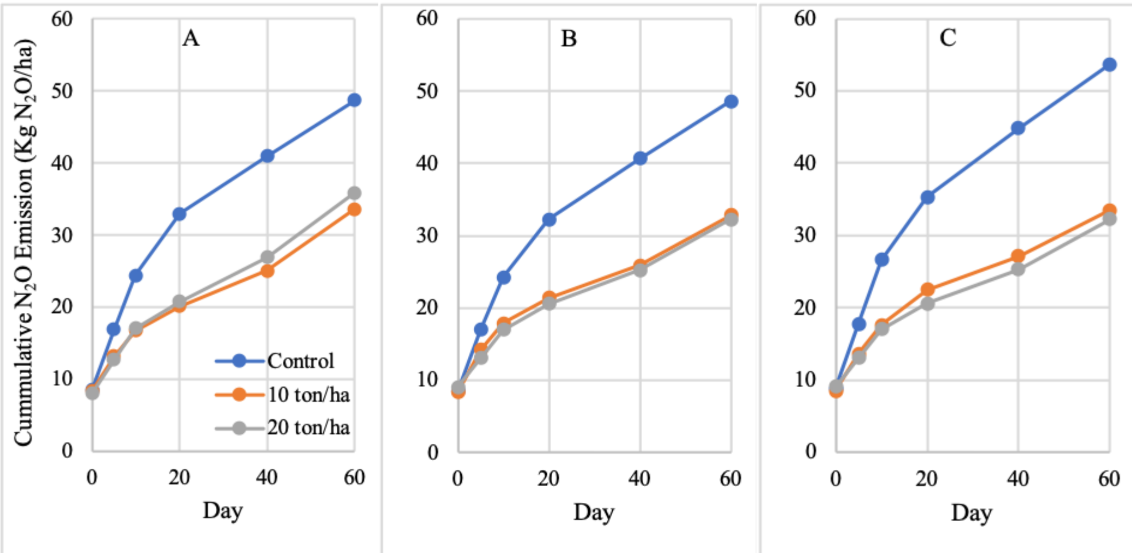

Figure 5. Cumulative N_2O gas emissions (kg N_2O/ha) from the control and the soils integrated with 10 and 20 tons/ha of biochar

3.5. Emissions of CH_4 from the soils

Figure 6 shows that the CH_4 gas emissions from the control soil without biochar addition and the addition of 10 and 20-ton/ha biochar are -0.0036±0.0008–0.0014±0.0005, -0.0025±0.0019–0.0029±0.0019 and -0.0029±0.0023–0.0043 ± 0.00017 kg CH_4/d/ha. Compared to control soils, the soils added with 10 and 20 tons/ha of biochar emit no significantly different amounts of CH_4 gas ($p > 0.05$). This demonstrates that adding biochar to the soils used in this investigation had no impact on CH_4 gas emissions. The similar outcome, where biochar and manure in the soil did not impact the release of CH_4 gas from the soil, was also reported by Abagandura *et al*. (2019).

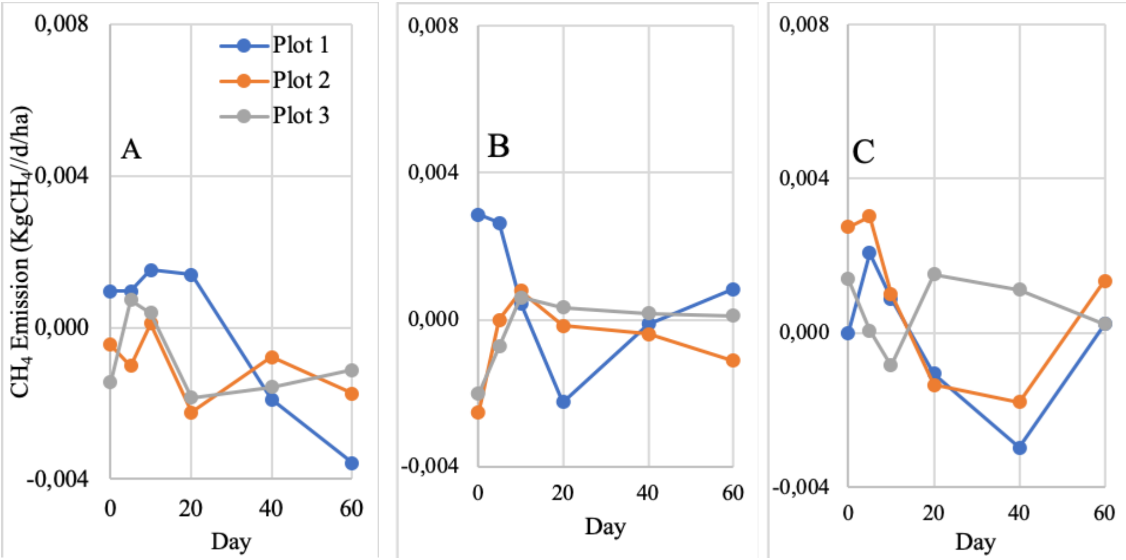

Figure 6. Emissions of CH_4 gas from the soil control (A), 10 (B) and 20 ton/ha (C) biochar incorporation into soils

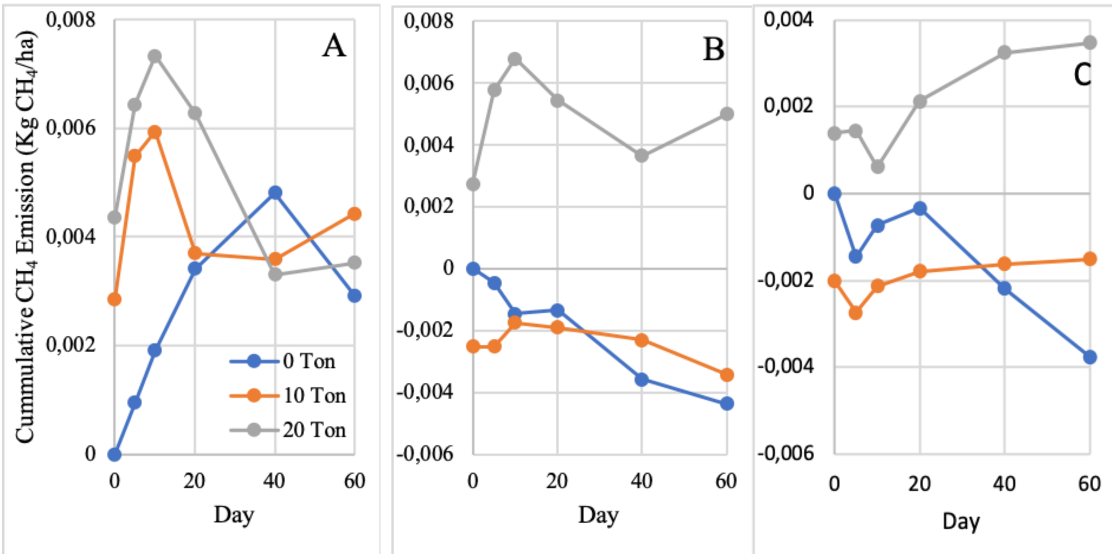

Figure 7. Cumulative CH_4 gas emissions (kg CH_4/ha) from the control and the soils integrated with 10 and 20 tons/ha of biochar

However, as can be seen from Figure 7 the cumulative CH_4 emissions do not show a consistent increase like CO_2 gas (Figure 3) and N_2O gas (Figure 5) as given in the previous section. The CH_4 emissions vary from positive (soil emits CH_4 gas) and negative (soil uptakes CH_4 gas). Similar results were also reported by Huang *et al*. (2019) and Lavesque *et al*. (2020). Large variations in CH_4 emissions indicate that the gas is actively utilized by soil microorganisms (Huang *et al*., 2019). The use of biochar may have reduced the number of methanotrophs that can utilise CH_4 and hence reduced CH_4 emissions. Biochar did not suppress methanogenic archaea, although a drop in the proportion of methanogenic to methanotrophic microbes resulted in variations in CH_4 gas emissions.

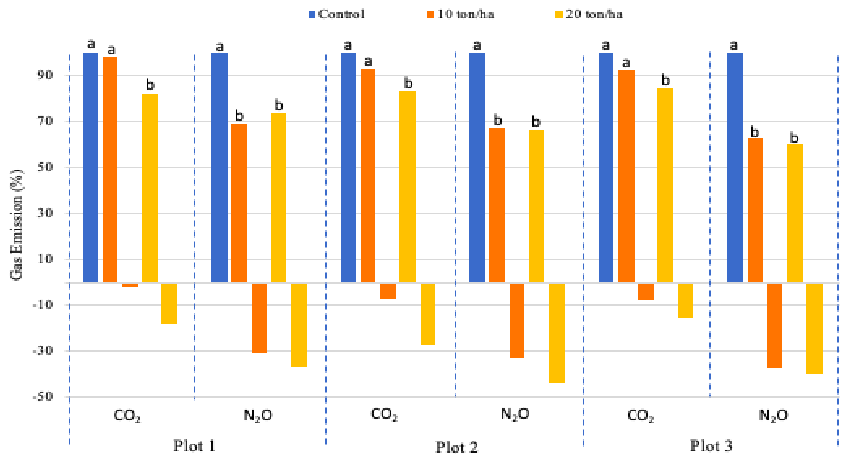

Figure 8. Cumulative CO_2 and N_2O emissions from soils incorporated with 10 and 20-ton/ha biochar and the control soils from three experimental plots given in percentages relative to the control soils, where the same letters at each emission bar indicate not significant (p > 0.05)

3.6. Cumulative CO_2 and N_2O emissions from the soils

The cumulative CO_2 and N_2O emissions from soils added with 10 and 20 tons biochar/ha are given in percentages and so direct comparison for both gases relative to the control soil are possible as given in Figure 8. Positive percentage means the gas is released from the soil (emission) and negative means the gas is absorbed back by the soils and reduces the measured gas percentage (Figure 8). So, it is possible to assess how well biochar is incorporated into the soil to reduce CO_2 and N_2O emissions. The letter above each bar in Figure 8 also indicates whether or not the corresponding emissions are considerably different (difference letters), or it is of no significance (the same letters). For all plots, the cumulative CO_2 emissions from the soil containing 10-ton/ha of biochar do not differ significantly from the control soils ($p < 0.05$). Shen *et al.* (2017) reported a similar finding, stating that the CO2 emissions were out of proportion to the amount of additional biochar. Furthermore, applying biochar at a higher rate could reduce soil respiration, which would lower CO_2 emissions during the growing season of maize, and stabilize microbial activity by slowing down mineralization rates because biochar has a higher C/N ratio. (Shen *et al.*, 2017).

The N_2O emissions exhibit the opposite trends at the same amount of biochar application rate (p > 0.05). However, the emission for both gases is significantly different from the control soils with the introduction of 20 ton/ha biochar ($p > 0.05$). The introduction of 10 and 20 ton/ha biochar, however, did not significantly lower the CO_2 emissions of all plots ($p < 0.05$). The N_2O emission, however, exhibits a divergent pattern ($p > 0.05$). The application of 10-ton/ha biochar significantly lowers the N_2O emissions when compared with a higher application rate (20 ton/ha biochar).

Variation responses of biochar addition on CO_2 and N_2O emissions particularly at the incorporation of 10-ton/ha biochar may indicate difference mechanisms responsible for the gases released from the soil. When treated with 10 and 20 tons/ha of biochar compared to a lower rate biochar application, it was discovered that the cumulative N_2O emission was greatly reduced (Lee *et al.*, 2022). According to a meta-analysis, the effect sizes for soil CO_2 emissions drastically dropped as biochar application rates were increased (He *et al.*, 2017).

4. Conclusion

The incorporation of 10 and 20-ton biochar per hectare decreased the emissions of CO_2 and N_2O up to 16.8% and 33.8%, respectively; whereas an uptake was observed for the CH_4 gas. The 10-ton/ha and 20-ton/ha biochar-incorporated soils emit much less CO_2 and N_2O than the control soils, but not significantly less CH_4. This result shows that incorporation of biochar to the soil of oil palm plantations is a potential strategy to lowering CO_2 and N_2O emissions from agricultural soils.

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