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Eco-Friendly Yield and Greenhouse Gas Emissions as Affected by Fertilization Type in a Tropical Smallholder Rice System, Ghana

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Abstract: Data on greenhouse gas emission levels associated with fertilization applied in smallholder paddy rice farms in Ghana are scanty. The current study investigated fertilization types to determine their eco-friendliness on yield, Global Warming Potential (GWP) and Greenhouse Gas Intensity (GHGI) in a major rice season in the forest zone of Ghana. In total, five treatments were studied viz Farmer Practice (BAU); Biochar + Farmer Practice (BAU + BIO); Poultry Manure + Farmer Practice (BAU + M); Biochar + Poultry Manure + Farmer Practice (BAU + BIO + M); and Control (CT). Fluxes of methane (CH_4) and nitrous oxide (N_2O) were measured using a static chamber-gas chromatography method. N_2O emissions at the end of the growing season were significantly different across treatments. BAU + BIO + M had highest N_2O flux mean of 0.38 $kgNha^{-1}day^{-1}$ (±0.18). BAU + M had the second highest N_2O flux of 0.27 $kgNha^{-1}day^{-1}$ (±0.08), but was not significantly different from BAU at $p > 0.05$. BAU+BIO recorded 0.20 $kgNha^{-1}day^{-1}$ (±0.12), lower and significantly different from BAU, BAU + M and BAU + BIO + M. CH_4 emissions across treatments were not significantly different. However, highest CH_4 flux was recorded in BAU+BIO at 4.76 $kgCH_4ha^{-1}day^{-1}$ (±4.87). GWP based on seasonal cumulative GHG emissions among treatments ranged from 5099.16 (±6878.43) to 20894.58 (±19645.04) for CH_4 and 756.28 (±763.44) to 27201.54 (±9223.51) $kgCO_2eqha^{-1}Season^{-1}$ for N_2O. The treatment with significantly higher yield and low emissions was BAU + M with a GHGI of 4.38 (±1.90) $kgCO_2eqkg^{-1}$.

Keywords: paddy rice; greenhouse gas emissions; global warming potential (GWP); greenhouse gas intensity (GHGI); methane (CH_4); nitrous oxide (N_2O); eco-friendly yield

1. Introduction

Agricultural systems represent a key source of Greenhouse Gas Emissions (GHGE) and contribute at least 12% to global anthropogenic emissions [1–3]. Paddy rice production forms a significant percentage of emissions that are generated from agricultural production systems and in Sub-Saharan African (SSA) agricultural systems have been cited as an area where GHGE are expected to grow due to a growing population and the need to grow more food to feed the increase in population [4,5]. Rice remains an important staple food for millions of households in SSA including Ghana where local production deficit has necessitated an intensification of local rice production. However, the production of rice is an important source of potent greenhouse gases including methane and nitrous oxide.

Emissions from paddy rice production are principally methane and nitrous oxide due to waterlogged field conditions (anoxic environment) and nitrogen fertilizer usage, respectively. Methane emissions from rice production alone accounts for an estimated 11% of anthropogenic emissions [5]. Over the past decade, a significant percentage (94%) of emissions from paddy rice production has emanated from developing countries. Asia leads with 90% of these emissions with an annual growth rate of 0.4–0.7% per year. The largest growth of emissions was recorded in Africa at 2.7% annually [6]. This growth in emissions is expected to increase as a response to high demand for rice to feed the growing population. There is therefore the need to sustainably intensify rice cropping systems to increase yields while reducing associated emissions [7]. The utilization of local materials, including Biochar from farm crop residues and poultry manure, has been touted to have the potential to provide a sustainable and cheap alternative to the conventional use of inorganic fertilization options in rice and other crop production [8–16].

An increasing demand on food to meet a growing population has meant a growing pressure on soils to sustain food production. Soil amendments, both organic and inorganic, has been extensively used to replenish lost soil nutrients to sustain production. Land management practices for rice productivity have been a key focus of research due to the opportunities that are available for substantial carbon sequestration and other GHG mitigation [17]. Paddy rice cultivation requires soil fertilization to ensure yield security and this practice is a key management factor that affects GHG emissions [11,18,19]. Various works that have been done on the effect of soil amendments on emissions confirm that management practices including soil amendment regimes can be efficiently managed to reduce emissions [20–22].

A quantitative review and analysis of fertilizer management practices on GHG emissions from rice cultivation systems by Linquist et al. [23] concluded that there is a positive correlation between fertilizer management practices and GHG emissions. The study suggested the need to investigate options for combining mitigation practices and also to determine the economic viability of these practices. Sampanpanish [24], studied the impact of organic and inorganic fertilizers on the emission levels of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The results of the study indicated a higher rate of emissions from chemical fertilizers when compared with emissions from organic fertilizers and therefore the use of organic fertilizers was recommended.

The objective of this study was to investigate the influence of organic and inorganic fertilization type on the yield, GWP, and GHGI of smallholder paddy rice firms in Ghana. We report that the use of organic soil amendment (poultry manure and Biochar) as components of conventional inorganic fertilizer use has a positive yield effect and also delivered the lowest emission per kilogram yield of rice (eco-friendly yield). In this paper, yields with low emissions per kilogram of yield are defined as eco-friendly.

2. Materials and Methods

2.1. Study Area and Experimental Design

The site selected for this research work was Nobewam (6.6237° N, 1.2940° W), a predominantly smallholder rice producing community in the Juaben Municipality of the Ashanti Region of Ghana. The community lies in the semideciduous forest zone of Ghana with diverse flora and fauna. The topography of the area is generally undulating, dissected by plains and slopes with heights ranging between 240 m and 300 m above sea level. The geology of the municipality is Precambrian rocks of the Birimian and Tarkwaian formations that are generally suitable for agriculture. The soils include the associations of the Kumasi-Offin, Bomso-Offin, Kobeda-Esshiem-Oda, Bekwai-Oda Compound, and Juaso-Mawso Compounds. The municipality experiences a bimodal rainfall pattern [25]. The weather data of the study area (mean precipitation and temperature) for 2019 from the nearest weather station are presented in Figure 1.

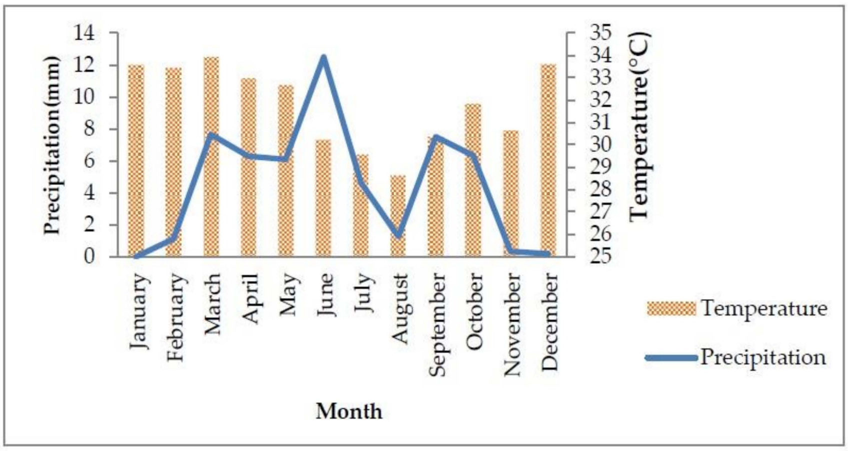

Figure 1. 2019 mean precipitation and temperature of study area.

The experiment was arranged as a randomized block design with 4 replications (Table 1) and the plot size was 2 m × 3 m for all treatments (Figure 2).

Table 1. Field design of study.

Block 1	Block 2	Block 3	Block 4
T3	T1	T2	T1
CT	T2	T1	CT
T4	T3	T3	T2
T2	T4	CT	T4
T1	CT	T4	T3

Figure 2. Field arrangement of treatment plots.

2.2. Fertilisation Types

In total, 5 soil fertilization treatments with 4 replicates were studied to measure their effect on emissions and yield of rice. The treatments were as follows:

1. Farmer Practice (BAU): This treatment represented the conventional means by which smallholder farmers cultivated rice in the study area. It was designated as Business as Usual (BAU) and the fertilizer application rate under this treatment was 300 kgha^{-1} of NPK as base and 50 kgha^{-1} urea (46%N) top-up.
2. Biochar (Bio) + Farmer Practice (BAU + Bio): the treatment represented Biochar and BAU soil amendment. A locally made ESLA stove made from a used lube barrel was used to char the

rice straw under anoxic conditions. Biochar was applied at 28,000 kg (28t) per hectare. In rice production, 28 tha^{-1} and 48 tha^{-1} represents 50% and 100% of rice straw produced in a single season, respectively. These two rates represent low and high amendment rates. An assumption was therefore made that, should a rice farmer convert at least 50% of his straw into Biochar and incorporate it on his farm, what will the effect be on yield and GHG emissions.

3. Poultry Manure (M) + Farmer Practice (BAU + M): For poultry manure, 1 tha^{-1}, 2 tha^{-1}, and 3 tha^{-1} represents low, medium, and high application rates, respectively. The high application rate of 3 tha^{-1} was selected for the current work.
4. Biochar + Poultry Manure + Farmer Practice (BAU + Bio + M): The fourth treatment was a combination of farmer practice, poultry manure and Biochar at the same application level as the single treatments.
5. Control treatment (CT): The control treatment did not have any soil amendments.

2.3. Greenhouse Gas (GHG) Sample Collection

Samples were collected using the static chamber method. The chamber and bases were designed and constructed according to the guidelines for measuring CH_4 and N_2O emissions from rice paddies by a manually operated closed chamber [26]. A polyvinyl chloride (PVC) bin (height = 72 cm, diameter = 53 cm) was converted to serve as the chamber. The choice of the bin for the chamber was based on its inertness to the target gases, lightweight, and ability to withstand breakage. The height was also able to accommodate matured rice plants without damaging it during sampling. The exterior of the chamber was coated white to prevent the effect of solar radiation. A sampling port fitted with a tube was made on the side of the chamber to collect gas samples. The tube was fitted to prevent artificial CH_4 ebullition when the chamber was mounted on the base during sampling. On top of the chamber were two additional ports, one to allow for chamber temperature measurement and the other to serve as a vent to prevent drastic changes in inside air pressure during chamber deployment [11]. Samples collection began 2 weeks before transplanting up until 2 weeks after harvesting. Sampling was done twice a week between 9 am and 12 pm with an increase in sampling frequency during fertilizer application and raining events. Samples were taken at 0, 10, and 20-time intervals.

2.4. GHG Sample Analysis

Analysis of gas samples was conducted using an appropriately fitted Gas Chromatograph-Scion GC456 (Scion Instruments, West Lothian, Scotland) with an electron capture detector (ECD) for N_2O detection at 350 °C and a flame ionization detector (FID) for CH_4 detection. Prepared samples were auto-injected into the gas chromatograph (GC) with a CTC PAL Combi-XT (CTC Analytics AG, Zwingen, Switzerland). N_2 was used as a carrier gas.

2.5. Flux Estimation and Statistical Analysis

Using the R statistical software (R version 3.6.1 (5 July 2019), the Revised Hutchison Mosier (HMR) model by Pedersen et al., [27] was used in calculating flux values for each treatment. The HMR model approaches flux estimation by modifying the classic nonlinear model (HM) proposed by Hutchinson and Mosier [28] to take into account horizontal gas transport through the soil or leaks in the chamber. This provides a robust method to analyze both linear and nonlinear data sets, a practical scenario depiction of gas transport inside a mounted static chamber on the field. The HMR model includes methods for automatic detection and analysis of linear data sets and data sets representing no flux. In total, 2 models were used to test for statistical significance as follows:

Model 1 < −lmer (Parameter ~ Treatments + (1|Reps), data = Flux, REML = FALSE)
Model 2 < −aov (Parameter ~ Treatments, data = Flux) key: Parameter = N_2O or CH_4.

Model 1 tested for differences in the random factors (Blocks) but indicated nonsignificance in all treatments. Model 2 was used to perform analysis of variance with means separated by Fishers Least

Significant Difference (LSD) at $p > 0.05$. Seasonal cumulative fluxes of CH_4 and N_2O were calculated by successive linear interpolation of estimated emission flux on successive sampling days with the assumption that the emissions followed a linear trend during nonsampling days [29].

2.6. Global Warming Potential (GWP) and Greenhouse Gas Intensity (GHGI)

For CH_4 and N_2O in this current work, the following equations were used in determining relevant GWP (kgCO_2-equivalent).

$$GWP_{CH4} = \text{C-}CH_4 \times 16/12 \times 25 \tag{1}$$

$$GWP_{N2O} = \text{N-}N_2O \times 44/28 \times 298 \tag{2}$$

where C-CH_4 and N-N_2O are gases fluxes (kgha^{-1}season^{-1}); 16/12 = ratio between the molecular mass of CH_4 and C; 44/28 = ratio between the molecular mass of N_2O and N; 25 is the Global Warming Potential (GWP) of CH_4 and 298 of N_2O [30,31].

Greenhouse Gas Intensity was calculated using the following equation;

$$GHGI = GWP/Y \tag{3}$$

where GWP is the global warming potential of CH_4 and N_2O emissions, and Y is the grain yield. Figure 3 summarizes the methodological phases of the current work.

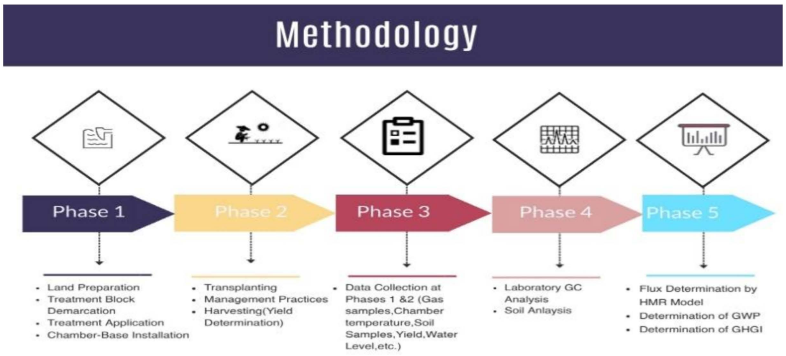

Figure 3. Depiction of methodology in phases.

3. Results

3.1. Average Daily Methane (CH_4) and Nitrous Oxide (N_2O) Emissions

The highest daily average for nitrous oxide emissions was observed in BAU + BIO + M (Table 2) and was significantly different from all treatments. Mean N_2O daily emission levels for T1 and BAU + M were not significantly different. The control treatment recorded the lowest N_2O emission levels.

Table 2. Daily mean emissions.

Treatment	Soil Amendment	N_2O (kgNha^{-1}day^{-1})	SD	CH_4 (kgCH_4ha^{-1}day^{-1})	SD
BAU	NPK (300 kgha^{-1} + 50 kgha^{-1}Urea (46%N))	0.22 ^{ab}	±0.09	1.10 ^{a}	±1.53
BAU + BIO	BAU + 28tha^{-1}Biochar	0.20 ^{b}	±0.12	4.76 ^{a}	±4.87
BAU+M	Manure (3tha^{-1}) + BAU	0.27 ^{ab}	±0.08	1.20 ^{a}	±1.77
BAU + BIO + M	BAU + Biochar + Manure	0.38 ^{a}	±0.18	1.57 ^{a}	±2.20
CONTROL	No amendment	0.02 ^{c}	±0.03	2.71 ^{a}	±2.77

^{a,b}: Values in the same row within same parameters followed by different letters are significantly different at $p > 0.05$ according to Fishers Least Significant Difference (LSD) post-hoc test for the separation of means.

3.2. Seasonal Cumulative Methane (CH_4) and Nitrous Oxide (N_2O) Emissions

Seasonal N_2O emissions ranged from 1.61 to 58.08 $kgN_2Oha^{-1}Season^{-1}$. BAU + BIO + M had the highest seasonal cumulative flux and was significantly different from all other treatments. Except the control treatment, BAU + BIO recorded the lowest seasonal flux mean for N_2O (Table 3).

Table 3. Mean seasonal cumulative emissions ($kgha^{-1}Season^{-1}$).

Treatment	N_2O	SD	CH_4	SD
BAU	39.93 ^{b}	±15.76	153 ^{a}	±206.35
BAU + BIO	26.84 ^{bc}	±29.04	626.83 ^{a}	±589.35
BAU + M	44.75 ^{b}	±10.28	169.18 ^{a}	±241.72
BAU + BIO + M	58.08 ^{a}	±19.69	230.94 ^{a}	±302.75
CONTROL	1.61 ^{c}	±1.63	389.53 ^{a}	±284.24

^{a,b,c}: Values in the same row within same parameters followed by different letters are significantly different at $p > 0.05$ according to Fishers LSD post-hoc test for the separation of means.

Early flux levels were observed in all treatments except the control approximately 13 days after the incorporation of manure and Biochar into the relevant plots. This represented the first peak for N_2O emissions during the season. Generally, a more consistent rise in N_2O emissions occurred between 8 DAT and 37 DAT peaking at 23 DAT, a day after the application of the first split of Nitrogen Fertilizer. The period between 8 DAT and 37 DAT also corresponded with the period of vigorous vegetative growth of the rice plants vis fresh root initiation, and minimum and maximum tillering (Figure 4).

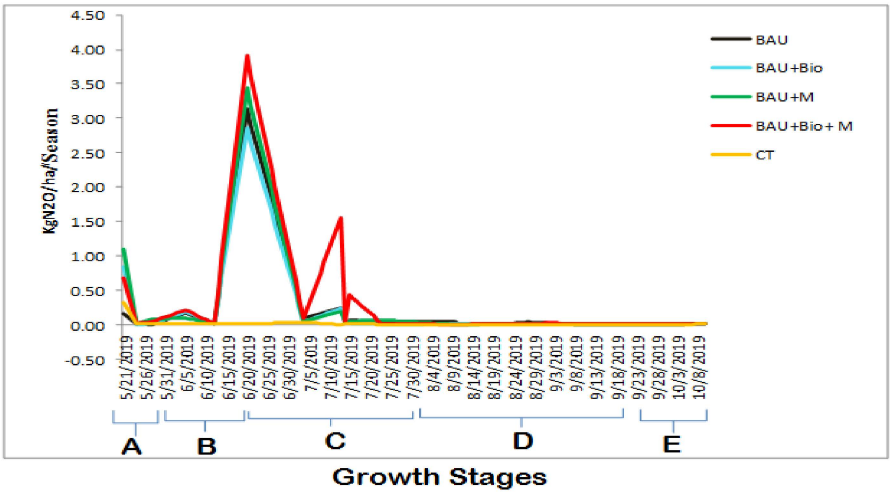

Figure 4. Seasonal cumulative nitrous oxide emissions. Key: A = Fallow Stage B = Vegetative Stage C = Reproductive Stage C = Ripening Stage E = After Harvest.

The seasonal cumulative methane emissions ranged between 153 and 626.83 $kgCH_4ha^{-1}Season^{-1}$ across treatments. Among treatments, seasonal CH_4 flux means were not significantly different. However, treatment 2 (BAU + BIO) recorded the highest seasonal mean. The control treatment recorded the second highest flux mean. Treatments 4 and 3 recorded the third and fourth highest seasonal flux means, respectively. The conventional farmer practice (BAU) recorded the lowest methane seasonal flux at 153 $kgha^{-1}season^{-1}$.

A total of 2 weeks (13 DAT) after the incorporation of Biochar and poultry manure into relevant plots, all treatments recorded negative methane fluxes except the control treatment.

Early but low peaks for methane flux across all treatments occurred between 3 DAT and 37 DAT (Figure 5). Between these periods, two rain days were recorded and fertilizer was applied to 22 DAT. The highest growing season methane peaks for all treatments occurred during the period when the rice plants neared maturity from the spikelet initiation stage to harvesting (37 DAT–100 DAT). This period also corresponded with the longest waterlogged period during the season.

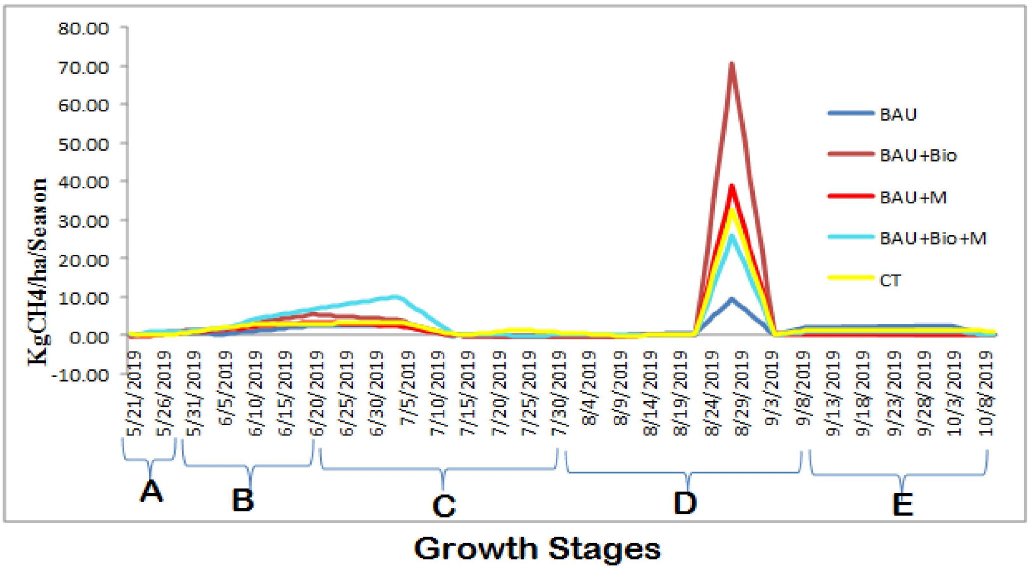

Figure 5. Seasonal cumulative methane emissions.

3.3. Global Warming Potential, Yield and Greenhouse Gas Intensity

Estimated net GWP based on seasonal cumulative GHG emissions among treatments ranged from 5099.16 to 20,894.58 and 756.28 to 27,201.54 $kgCO_2eqha^{-1}Season^{-1}$ for CH_4 and N_2O, respectively (Table 4). The contribution of N_2O emissions to net GWP was higher, between 70 to 80%, than CH_4 in all treatments except BAU + BIO and control treatment (CT) which contributed dominant methane GWP of 68% and 96%, respectively.

Table 4. Seasonal Global Warming Potential (GWP), yield, and Gross Greenhouse Gas Intensity (GHGI).

	Net Seasonal GWP ($kgCO_2eqha^{-1}$ $Season^{-1}$)				Gross Seasonal GWP ($kgCO_2eqha^{-1}$ $Season^{-1}$)		Yield ($Kgha^{-1}$)		Gross Greenhouse Gas Intensity (GGHGI) $kgCO_2eq$ kg^{-1}	
Treatment	**N_2O**	**SD**	**CH_4**	**SD**	**GGWP**	**SD**	**YIELD**	**SD**	**GGHGI**	**SD**
BAU	18,698.64 ^{ab}	±7383.78	5099.16 ^{a}	±6878.43	23,797.82 ^{a}	±7411.43	5290.83 ^{b}	±222.36	4.49 ^{b}	±1.40
BAU + BIO	12,571.13 ^{bc}	±13602.96	20,894.58 ^{a}	±19,645.04	33,465.63 ^{a}	±21,002.97	5318.33 ^{b}	±148.49	8.19 ^{a}	±1.25
BAU + M	20,959.88 ^{ab}	±4814.37	5639.33 ^{a}	±8057.59	26,599.22 ^{a}	±11,562.23	6070.00 ^{a}	±323.19	4.38 ^{b}	±1.90
BAU + BIO + M	27,201.54 ^{a}	±9223.51	7698.25 ^{a}	±10,091.92	34,899.80 ^{a}	±18,620.33	5935.83 ^{a}	±332.68	6.35 ^{ab}	±0.94
CONTROL	756.28 ^{c}	±763.44	12,984.58 ^{a}	±9474.70	13,740.86 ^{a}	±9609.36	4395.00 ^{c}	±301.28	3.13 ^{b}	±2.19

^{a,b,c}: Values in the same row within same parameters followed by different letters are significantly different at $p > 0.05$ according to Fishers LSD post-hoc test for the separation of means.

Treatments BAU + M and BAU + BIO + M had the highest yield and were not significantly different from each other but significantly different from treatments BAU, BAU + BIO, and BAU + M. Treatments BAU and BAU + BIO recorded the second highest yields which were not significantly different from each other. The yields from BAU and BAU + BIO were similar to yield levels reported by farmers in the study area (5.0 $tha^{-1}season^{-1}$). BAU + M and BAU + BIO + M had yields higher than the mean yields of the experimental area. The control treatment recorded the lowest yield among all treatments.

4. Discussion

There were relatively no CH_4 emissions at the beginning of the season among all the treatments and this trend continued up till the third day after seedlings were transplanted. An increase in the CH_4 emission rates across treatments was observed from 8 DAT when there was the initiation of fresh roots with the emissions peaking (1st peak) around the tillering stage of the rice plants at around 30 DAT. The reason for this peak may primarily be as a result of the development of anoxic soil conditions and the growth of rice plants. For methane to be produced methanogenesis must occur under strictly anaerobic conditions and this stage (8 DAT–30 DAT) of the season provided the ideal conditions. After the production of methane, its emission was likely to have been facilitated by the early growth of the rice plants. Two key pathways exist for the emission of CH_4 from paddy fields [32]. The pathways are through the aerenchyma tissue of the rice plants or through ebullition of methane laden gas bubbles when the soil is disturbed physically when field is inundated or by soil internal dynamics [33–36]. The rice growth factor in the first observed methane peak was key as plant mediated gas transport constitutes over 90% of emissions as root development and vegetative growth commences [37–40].

The reasons above is further buttressed when during the near maturity stages of the rice plants between 80 to 99 DAT, the second and highest methane peak was observed for all treatments. This period corresponded with high water levels across all treatment plots and also the most developed period of the rice plants with 14 days remaining to final drainage before harvesting. Furthermore, the observed second peak is attributable to the significant availability of litter and root exudates during this advanced vegetative stage of the rice plants. The availability of litter and root exudates provides additional carbon sources which increases the availability of substrates for methanogens for methane production and emission [41]. At this late stage of the rice plants, the efficiency of emissions through the plants is also enhanced because of a well-developed aerenchyma system, the key physiological factor in rice plants that emits methane.

The microbial processes of nitrification and denitrification in the soil produce N_2O. The process of nitrification is anaerobic while denitrification is anaerobic, however, they are all dependent on the availability of carbon sources and the addition of organic and/or inorganic soil amendments increases the carbon source and enhances microbial activity leading to the production and emission of N_2O [42,43].

The first peak for N_2O emissions was observed 17 days after the incorporation of poultry manure and Biochar into relevant treatment plots. There was an immediate significance in the differences observed in nitrous oxide emissions among the treatments that had poultry manure incorporated and those without it. The reason for the observed differences in the first N_2O peak was the availability of mineral N to soil microbes in the treatment plots as a result of the application of poultry manure. N_2O emission from soil has frequently been reported after N fertilization [31,44,45].

The second and highest peaks for N_2O emissions across all treatments coincided with the periods of first and second split fertilizer application and panicle development, during which there is vigorous vegetative growth of the rice plants. In addition to the attribution of high emissions to high availability of mineral N for enhanced microbial activity, the vegetative period also contributes carbon through root exudates which nourishes the microbes responsible for nitrification/denitrification. Increased N mineralization during the maturity stages of the rice plants has also been strongly cited as a key factor for the observation of high N_2O peaks [46–48]. The reported flux levels for both N_2O and CH_4 in this current study is among the maiden efforts to quantify emissions from smallholder rice paddy farms in Ghana and as such there is paucity in works to locally compare results. However, the flux rates quantified are within reported ranges from works from other geographical areas with similar environmental and climate conditions.

The current study reported cumulative seasonal methane emissions of between 153 to 626 $kgha^{-1}$ which is similar to works in Vietnam by [3], who reported seasonal methane emissions of between 148 to 627 $kgha^{-1}$. In India, Khosa et al. [1] reported seasonal averages of 113–290 $kgha^{-1}$.Wassmann et al. [21] have also reported seasonal fluxes for methane up to 600 $kgCH_4ha^{-1}Season^{-1}$ from tropical and subtropical Asian paddy systems. In Zimbabwe, Nyamadzawo et al., [49] reported seasonal averages for N_2O emissions among treatments at 0.28 $kgha^{-1}$ and this is similar to the treatment average of 0.27 $kgha^{-1}$ reported in this current study. In China where high nitrogen fertilizer rates are used, Liu et al. [50] reported higher seasonal averages for N_2O emissions at 0.45 $kgha^{-1}$. Kim et al. [51], in their synthesis of available data on greenhouse gas emissions in natural agricultural croplands including paddy fields in Sub-Saharan Africa, saw N_2O emissions ranging between 0.05 to 112.0 $kgha^{-1}season^{-1}$.

Nitrous oxide is produced through the microbial processes of aerobic nitrification and anaerobic denitrification. These processes are enhanced when nitrogen fertilizer and/or organic matter is amended into soils as it provides a C source for the microbial processes [41]. Under the current study, T2, which was an integrated treatment of (NPK 300 $kgha^{-1}$ + Urea (46%N) at 50 $kgha^{-1}$) and Biochar (28tha^{-1}) recorded the lowest N_2O flux compared to the treatments with only inorganic fertilizer amendments and those with poultry manure. This finding is consistent with the works of Shen et al. [52] and Cayuela et al. [53] who have reported that the addition of Biochar reduced N_2O emissions in paddy fields. Various explanations have been proffered as reasons why Biochar reduces N_2O emissions. Kindaichi et al., [54] and Das et al., [29] reported that the ability of Biochar to increase the C:N ratio in soils allows for heterotrophic bacteria which are subject to N limitation to compete with nitrifiers for available nitrogen. Typically, heterotrophic bacteria grow faster and are more abundant in soils than nitrifying bacteria. This gives the heterotrophic bacteria advantage over nitrifiers in utilization of available nitrogen, consequently reducing N_2O production due to decreased nitrification rates. Low N_2O emissions from Biochar-amended soils might also be due to the absorption of NH4+ by Biochar with a consequent decrease in soil NH4+ availability, which may limit both nitrification and denitrification [24,55]. The negative effect of Biochar on N_2O emissions has also been reported to be as a result of its action on soil physical properties by improving soil porosity, enhancing aeration and also adsorbing excess soil moisture [56,57]. Biochar amended to soils have also been found to have a significant initial noxious effect on soil microbial communities [58,59] due to its potential carrying of toxic organic compounds (polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins and furans, which develops during the pyrolysis process of biomass [60,61]. The mechanism of these inherent toxic compounds is highly likely to alter microbial processes including nitrification and denitrification [62–64]. The release of these toxic compounds after Biochar is amended into soils has been posited as a mechanism that leads to low N_2O emissions in Biochar amended soils [60,65,66]. The integrated treatments, BAU + M and BAU + BIO + M that had poultry manure (PM) as constituents, recorded the highest and second highest mean flux rates, respectively (Table 3). This is explained by the low C:N ratio typical of Poultry manure unlike Biochar. The incorporation of PM therefore promotes the rapid release of N needed for the microbial processes of nitrification and denitrification for high N_2O emissions. The addition of organic manure also creates the ideal conditions for denitrifying bacteria to thrive as decomposing organic matter increases available labile C for denitrification to occur thereby increasing N_2O emissions [10]. These reasons could explain why the treatments with PM had higher N_2Oflux means than the other treatments without PM.

Research on the effect of Biochar on methane emissions in rice paddies has been varied with no definite conclusions on its CH_4 emission reduction abilities [13,67]. Some research works have reported reductions in soil CH_4 emissions as a result of Biochar amendment [68–71], others have also reported an increase in emissions [63,72]. There has also been reports that indicated no significant effects on CH_4 emissions from Biochar-amended soils [73]. In this current study, there were no significant differences in CH_4 emissions among treatments (Table 3). However, treatment 2 recorded the highest seasonal mean for methane emissions (Table 3). This may be explained by a number of factors including the pH dynamics in the soil after Biochar was incorporated.

High pH, which is typical of Biochar, produces a liming effect on soils into which it is incorporated [74,75]. Methanogens, the microbes that produce methane thrive optimally at pH levels between 6 to 8, whilst methanotrophs that consume methane thrive well in more acidic soils [76], thus, the methane mitigating effect of Biochar is more pronounced in acidic soils where methanotrophy is enhanced. In the current study, it was observed that pre-experiment average soil pH of 5.44 increased to an average of 6.78 at the end of the 123-day growing in all treatment plots, seen in Appendix A Table A1. This indicates that the change in pH enhanced the activities of methanogens in the soil leading to a high rate of methanogenesis and consequently methane production and emission. The Biochar treatment (BAU + BIO) had a higher CH_4 mean which led to a higher GWP than all the other treatments. Further, with rice straw having been found to have a positive effect on CH_4 emissions [14,77,78], years of its incorporation into the soil by farmers as a conventional local practice is likely to have built up a large pool of highly labile organic matter whose coupling with the observed decrease in soil pH led to enhanced methanogenesis. This may account for the high methane levels observed in the control plots. The reasoning above is consistent with the work of Cui et al. [79], who reported a substantial increase in CH_4 production after straw application in a paddy system.

The effect of Biochar and poultry manure amendment on rice yield was recognizable in the current study. The two treatments (BAU + M and BAU + BIO + M) that had Biochar and manure as components yielded significantly higher rice grains compared to other treatments without them (Table 4). The role of Biochar in the high yield recorded, is explained by its ability to directly supply nutrients such as Ca, Mg, K, and P whilst enhancing their uptake due to high electrical conductivity (EC) values typical of Biochar [9,18,80,81]. EC values are an indicator of the amount of water-soluble nutrients and as a consequence, the improved soil nutrient content in the soil coupled with high water solubility will enhance nutrient uptake and have a positive effect on plant growth and yield. The poultry manure component of treatments 3 and 4 also is also likely to have had an added positive effect on plant growth and yield. Poultry manure has been found to provide a balanced supply of both micro and macro nutrients. Pronounced microbial activity in poultry manure is also able to improve the physico-chemical properties in soils [67,82].There have been numerous reports that are consistent with results of the current study regarding the positive yield effect of Biochar and poultry manure as stand-alone soil amendments or in combination with inorganic fertilizers [79,83–86]. In the current study, which was carried out in the major season (March/April–August/September) of rice production in the experimental area, the percentage contribution of N_2O was higher (70–80%) than that of CH_4 emissions across all treatments except (BAU + BIO) and control. The cumulative seasonal GHG estimation showed that N_2O had more peaks than CH_4 emissions (Figures 3 and 4). The high N_2O GWP contribution reported in this current study, is at variance with numerous reports on paddy systems where CH_4 emissions the dominant GHG contributing highest to seasonal and yearly GWP [47,87,88]. These findings have predominantly emanated from temperate irrigated paddy systems where there is control over flooding events. These areas are also highly variable regarding climatic, environmental and management factors to what pertains in Sub-Saharan Africa. These climatic and management factors to a significant extent determine the levels of emissions that emanate from rice paddies [13,89–94]. It is therefore currently difficult to make robust comparisons with findings from the temperate regions where majority of these reports emanate from. Richards et al. [95] agrees with this difficulty, when they reported in their work that there may be poor emissions estimates in tropical developing countries when GHG calculated on temperate conditions factors are employed as a basis for comparing and/or estimating tropical African emissions.

In India, Kritee et al. [96] reported high nitrous oxide emissions in intermittently flooded rice fields and posited that previous estimates may have underestimated earlier estimates by between 30 to 45 times. The reported N_2O emissions in their study in the Indian sub-continent ranged between 0 to 33 $kgha^{-1}$. The highest N_2O flux from their work was recorded from fields that underwent multiple aeration periods. The field condition under this current study is similar to the Indian experimental condition and with inorganic fertilizer application rate of 350 $kgha^{-1}$ plus poultry manure amendments, it is not unusual to have recorded high N_2O emissions in the current study. The authors further concluded that rainfed farms are at risk for elevated rice-N_2O emissions. In a study by Nyamadzawo et al. [49] the authors recorded low seasonal CH_4 emissions in Zimbabwe and indicated that rain-fed paddy systems may be a weak source for CH_4 emissions.

It is established that the water regime in a paddy system is the most important factor that controls the CH_4 and N_2O emission levels [2,97–100]. With high dependence on rain coupled with weak to nonexistent irrigation infrastructure in Ghana's paddy rice systems to manage water, low rainfall levels coupled with high temperatures mean that fields quickly dry out reducing the anoxic soil conditions required for methanogenesis. For the period of this experiment, two rain days were recorded with an average above soil water level of 0.8 cm across treatment plots enhancing the aerobic field conditions necessary for the microbial processes of nitrification and denitrification. The amendment of the soil with poultry manure together with the inorganic fertilizers may also have accounted for the high N_2O emissions which led to higher seasonal N_2O GWP. In the current study, the treatments that had poultry manure and/or inorganic fertilizer as component soil amendment had significantly higher seasonal emissions levels (Table 3). Akiyama and Tsuruta [8] reported high N_2O emissions associated with poultry manure when they investigated the effect of poultry and swine manure on Nitrous oxide, NO, and N_2O fluxes.

The effect of Biochar and poultry manure amendment on rice yield was recognizable in the current study. The two treatments (BAU + M and BAU + BIO + M) that had Biochar and manure as components yielded significantly higher rice grains compared to other treatments without them (Table 3). The role of Biochar in the high yield recorded, is explained by its ability to directly supply nutrients such as Ca, Mg, K, and P whilst enhancing their uptake due to high electrical conductivity values typical of Biochar [9,80,83,86,101]. EC values are an indicator of the amount of water-soluble nutrients [82]. As a consequence, the improved soil nutrient content in the soil coupled with high water solubility will enhance nutrient uptake and have a positive effect on plant growth and yield. The poultry manure component of treatments 3 and 4 is also likely to have had an added positive effect on plant growth and yield. Poultry manure has been found to provide a balanced supply of both micro and macro nutrients. Pronounced microbial activity in poultry manure is also able to improve the physico-chemical properties in soils [47,88,102]. There have been numerous reports that are consistent with results of the current study regarding the positive yield effect of Biochar and poultry manure as stand-alone soil amendments or in combination with inorganic fertilizers [89,90].

The peculiar nature of most rainfed paddy system in SSA where there is very little control on water management may predispose smallholder paddy production to high N_2O emissions. In this study, the contribution of N_2O emissions to GWP shows that smallholder production systems are likely to be a key source of higher than currently anticipated N_2O emissions. The integrative amendment of soil with organic materials, poultry manure, and Biochar enhanced crop performance and delivered low greenhouse gas intensity in one scenario in the current study.

5. Conclusions

The utilization of organic soil amendments viz Biochar and poultry manure as components of the conventional inorganic means of soil amendments proved to have a positive effect on rice yield. The integrated approach of combining organic and inorganic fertilizers used in this study was effective in delivering higher yields than the conventional practice of farmers alone, particularly, poultry manure use as a component soil amendment. This gives a strong indication of the feasibility of organic fertilizer as a sustainable means of augmenting inorganic soil amendments for increased rice yield. Biochar produced from straw as was the case in this study provides a sustainable means of managing waste after harvest and reduces the tendency of farmers to burn harvest residue which pollutes the environment.

The determination of a sustainable production system in terms of emissions is the ability of that system to produce less emission per kilogram of yield. Higher yields offset the emissions associated with a production system. The objective of this work was to determine a soil fertilization option that could produce high yields with low emissions (eco-friendly yield). The fertilization option of poultry manure and conventional inorganic fertilizer (BAU + M) recorded the lowest emission per kilogram of yield. This work concludes that the continuous use of poultry manure in combination with the BAU practice of farmers will likely lead to improvements in yield and lead to reductions in the emissions per kilogram of yield (eco-friendly yields).

This work was limited by the unavailability of funding support to conduct a multiple season study to determine the long-term effects of the studied treatments. It is therefore recommended that a multiseasonal study is conducted to determine the long-term effects of especially the (BAU + M) fertilization type on smallholder rice yield and emissions to determine its suitability for scaling.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Soil parameters.

Labels	pH 1:2.5	%	% Total	% Organic	Exchangeable Cations cmol/kg				cmol/kg	cmol/kg	cmol/kg	%	AVi.BRAYS	Mechanical Analysis		
		O.C	**NITROGEN**	**MATTER**	**Ca**	**Mg**	**K**	**Na**	**T.E.B**	**EX. ACIDITY**	**ECEC**	**Base Sat.**	**ppmP**	**% Sand**	**% Silt**	**% Clay**
Soil Parameters Before Study	5.442	1.37	0.12	2.36	2.96	1.32	0.99	0.05	5.32	0.74	6.05	86.84	1.40	48.00	32.40	19.60
Soil Parameters After Harvesting																
BAU(T1)	6.84	0.88	0.0532	1.51	8	1.4	0.495	0.0782						46.96	31.28	21.76
BAU+Bio(T2)	6.8	0.88	0.0504	1.51	7	3.4	2.027	0.15						58.38	19.50	22.12
BAU+M(T3)	6.72	0.84	0.0504	1.44	5.6	3.2	0.561	0.12						49.32	28.92	21.76
BAU+M+Bio(T4)	6.77	1.08	0.049	1.86	7.4	1.2	2.093	0.15						50.96	27.64	21.40
Control(T5)	6.77	0.6	0.0532	1.03	5.4	2.6	0.561	0.15						76.40	9.28	14.32

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