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BIOCHAR AND N-FERTILISATION EFFECTS ON GREENHOUSE GASES EMISSIONS AND PRODUCTIVITY OF LOW LAND RICE

A thesis, in the Rural Polytechnic Institute of Training and Applied Research (IPR/IFRA) in partnership with the West African Science Service Centre on Climate Change and Adapted Land use (WASCAL), submitted in partial fulfilment of the requirement for Doctor of Philosophy in Climate Change and Agriculture of the University of Sciences, Techniques and Technologies of Bamako (USTTB)

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BIOCHAR AND N-FERTILISATION EFFECTS ON GREENHOUSE GASES EMISSIONS AND PRODUCTIVITY OF LOW LAND RICE

BY

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MAY, 2023

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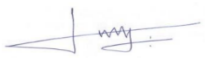

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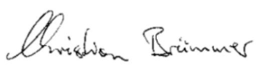

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Dedication

This work is dedicated to my late elder brother, Mr Iboko, Chukwudi Jeremiah, under whose tutelage I developed keen interest in reading and research.

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I am immensely grateful to all my supervisors, Dr Niaba Teme, Dr Dossou-Yovo Elliott, Dr Brummer Christian and prof Sunday Obalum for their great guidance and contribution towards the success of this study. I am thankful to the members of the jury that examined the work, the reviewers (examiners) for their suggestions and comments for the improvement of the work. I am also grateful to the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) for providing the funding for this research and to Africa Rice research centre for hosting the research and for their support during the field work. Indeed, I am also thankful to my field assistants: Desire, Prisca, Olivia and Brice for their dedications during the field data collections.

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List of acronyms and abbreviations

C	Carbon
N_2O	Nitrous Oxide
CH_4	Methane
GHG	Greenhouse Gas
FAO	Food and Agricultural Organization
GRISP	The Global Rice Science Partnership
CO_2	Carbon di oxide
USDA	United Start Department of Agriculture
N	Nitrogen
FTIR	Fourier Transform Infrared Spectroscopy
XRD	X-ray Diffraction
SEM	Scanning Electron Microscopy
TGA	Thermo-gravimetric Analysis
BET	Brunauer-Emmet-Teller Analysis
EDS	Energy Dispersive Spectroscopy
HTT	Highest Treatment Temperature
SA	Stable Agreggate
CEC	Cation Exchange Capacity
SOM	Soil Organic Matter
EC	Electrical Conductivity
RCBD	Randomized Complete Block Design
OC	Organic Carbon
GHGI	Greenhouse Gas Intensity
GWP	Global Warming Potential
DAS	Days After Seeding
FID	Flame Ionization Detector
ECD	Electron Captor Detector
IPCC	Inter-government Panel on Climate Change
GS	Growth Stage
IRRI	International Rice Research Institue
ANOVA	Analysis of Variance
HSD	Honest Significant Difference

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Résumé

La rizière est une source importante de méthane (CH_4) et d'oxyde nitreux (N_2O) qui provoque le réchauffement climatique. Il a été rapporté que le biochar atténue l'émission de ces gaz. Cependant, son efficacité en co-application avec de l'azote (N) et sans travail du sol est largement inconnue. Nous avons mené une étude de deux ans au centre de recherche d'AfricaRice à Bouaké, en Côte d'Ivoire, pour étudier le potentiel de l'application combinée de biochar et d'engrais azotés (N) pour atténuer les émissions de N_2O et de CH_4 et améliorer le rendement du riz sur les terres basses et les propriétés du sol sans travail du sol. Une conception en bloc complètement randomisée composée de 12 traitements et de trois répétitions a été utilisée. Traitements inclus : témoin (C1N2, travail du sol avec houe + 120 kgN/ha), faible biochar (B1, biochar à 3 t/ha), fort biochar (B2, biochar à 6 t/ha), biochar activé (BA, biochar à 3 t/ha + bouse de vache à 5 t/ha), N moyen (N2, 120 kgN/ha), N élevé (N3, 180 kgN/ha), biochar faible et faible N (B1N1, biochar à 3 t/ha + 60 kgN/ha), faible biochar et moyen N (B1N2, biochar à 3 t/ha + 120 kgN/ha), faible biochar et fort N (B1N3, biochar à 3 t/ha + 180 kgN/ha), fort biochar et bas N (B2N1, biochar à 6 tonnes/ha + 60 kgN/ha), haut biochar et moyen N (B2N2, biochar à 6 t/ha + 120 kgN/ha), haut biochar et haut N (B2N3, biochar à 6 t/ha + 180 kgN/ha). Les résultats ont indiqué que la biomasse de paille de riz était la plus sensible à l'application du traitement. C1N2 a enregistré la plus forte émission cumulée de CH_4 (195,04 kg/ha) tandis que la plus faible émission de CH4 (98,15 kg/ha) a été observée à BA. L'application de N a amélioré les émissions de CH4 par rapport au biochar, mais le biochar a favorisé les émissions de N2O. B2N2 a produit les émissions de N2O les plus élevées (4,14 kg/ha) tandis que les émissions de N2O les plus faibles (0,48 kg/ha) se sont produites dans B1. L'activation du biochar avec de la bouse de vache, BA n'a déclenché aucun changement majeur dans les émissions de CH_4 ou de N_2O par rapport à B1, mais a considérablement réduit le GWP et le GHGI par rapport à C1N2. Par rapport à B2N2 et B2N3, le GWP, les GHGI et la séquestration du carbone ont été significativement diminués par B1. L'augmentation du biochar a augmenté la séquestration du carbone. Plus encore, l'augmentation de N avec ou sans biochar a progressivement augmenté le rendement du riz, tandis que l'augmentation du biochar seul sans N de B1 à B2 a diminué le rendement du riz. B2N3 et B2N2 ont tous deux considérablement amélioré le rendement du riz plus que C1N2. En revanche, l'augmentation du biochar sans N, de B1 à B2 a augmenté l'indice de récolte de riz similaire à BA. Des corrélations faibles et positives ont été trouvées entre les traits morphologiques du riz et les émissions de GES ainsi que les émissions de GES et le rendement du riz. Quels que soient les taux, ni

l'application de biochar avec ou sans N ni l'application de N avec ou sans biochar n'ont eu d'impact significatif sur les propriétés du sol. En conclusion, l'application de N avec le biochar a réduit les émissions de GES, séquestré le carbone et amélioré le rendement du riz par rapport aux pratiques de gestion actuelles des agriculteurs. B2N3 est un candidat à l'adoption par les agriculteurs en raison de son potentiel de rendement élevé en riz et de son respect relatif de l'environnement.
Mots clés : serre, protoxyde d'azote, méthane, émission, paddy, rendement, biochar

Abstract

Paddy field is an important source of methane (CH_4) and nitrous oxide (N_2O) which causes global warming. Biochar has been reported to mitigate the emission of these gases. However, its efficacy under co-application with nitrogen (N) and zero tillage is largely unknown. We conducted a two-year study at AfricaRice researcher centre Bouake, Cote Divoire to investigate the potential of combined biochar and nitrogen fertiliser (N) application in mitigating N_2O and CH_4 emissions and improving low land rice yield and soil properties under no tillage. A completely randomized block design composed of 12 treatments and three replications were used. Treatments included: control (C1N2, tillage with hoe + 120 kgN/ha), low biochar (B1, biochar at 3 t/ha), high biochar (B2, biochar at 6 t/ha), activated biochar (BA, biochar at 3 t/ha + cow dung at 5 t/ha), medium N (N2, 120 kgN/ha), high N (N3, 180 kgN/ha), low biochar and low N (B1N1, biochar at 3 t/ha + 60 kgN/ha), low biochar and medium N (B1N2, biochar at 3 t/ha + 120 kgN/ha), low biochar and high N (B1N3, biochar at 3 t/ha + 180 kgN/ha), high biochar and low N (B2N1,biochar at 6 ton/ha + 60 kgN/ha), high biochar and medium N (B2N2, biochar at 6 t/ha + 120 kgN/ha), high biochar and high N (B2N3, biochar at 6 t/ha + 180 kgN/ha). Findings indicated that rice straw biomass was most responsive to treatment application. C1N2 recorded highest cumulative CH_4 emission (195.04 kg/ha) while lowest CH_4 emission (98.15 kg/ha) was observed in BA. N application enhanced CH_4 emission than biochar but biochar promoted N_2O emissions. B2N2 produced highest N_2O emission (4.14 kg/ha) while the lowest N_2O emission (0. 48 kg/ha) occurred in B1. Activation of biochar with cow dung, BA did not trigger any major change in either CH_4 or N_2O emission compared to B1 but significantly decreased GWP and GHGI compared to C1N2. Relative to B2N2 and B2N3, GWP, GHGI and carbon sequestration were significantly decreased by B1. Increasing biochar increased carbon sequestration. More so, increasing N with or without biochar progressively increased rice yield whereas increasing biochar alone without N from B1 to B2 decreased rice yield. B2N3 and B2N2 both significantly promoted rice yield more than C1N2. In contrast, increasing biochar without N, from B1 to B2 increased rice harvest index similar to BA. Weak and positive correlations were found between rice morphological traits and GHG emissions as well as GHG emission and rice yield. Regardless of rates, neither the application of biochar with or without N nor the application of N with or without biochar significantly impacted soil properties. Co-application of N application with biochar decreased GHGs emissions, sequestered carbon and improved rice yield over the current farmer's management practices.

B2N3 is an adoption candidate by farmers due to its high rice yield potential and relative environmental friendliness.

Key words: greenhouse, nitrous oxide, methane, emission, paddy, yield, biochar

CHAPTER ONE

1.0. INTRODUCTION

Globally, rice (*Oryza sativa* L.) is an important staple. About 3 billion people around the world depend on it for their daily calory intake (Nguyen and Ferrero, 2006; Fahad et al., 2019). Consequently, more than 450 million metric tons of milled rice (Muthayya et al., 2014) are consumed annually, with a projected increase in consumption to about 551 million tons by 2030 (Saito et al., 2017). This high consumption rate makes rice a strategically important food crop for combatting current and future global hunger and malnutrition.

Asia and Africa account for most of the rice consumed globally. It is estimated that about 90% of the global rice production and consumption take place in Asia (Fukai and Wade, 2021; Maraseni et al., 2018) and Africa, particularly in West Africa (Niang et al., 2017). In these two continents, rice constitutes an integral part of the daily diet (GRiSP, 2013) and consumption can reach as high as 100kg per person per annum (Fahad et al., 2019) compared to average global per capita rice consumption of 64 kg (Bhandari, 2019). Although the per capita rice consumption is expected to decrease in Asia, it is however projected to increase in Africa and other regions of the world (Saito et al., 2017). It is estimated that by 2035, the global rice production will need to increase by more than 30 Mt (Fahad et al., 2019) to meet the population-induced increase in rice demand (Muthayya et al., 2014; Rodenburg and Saito, 2022).

In West Africa, apart from population growth, the growth in rice demand has also been partly attributed to urbanization (Mendez del Villar and Lançon, 2015). These combined demand forces have caused a sharp rise in the annual per capita rice consumption in the region from 10kg in the early 60s to about 54kg in 2000s (Soullier et al., 2020). This increase in demand has resulted in a deficit between rice production and demand (Soullier et al., 2020).

Rice production has significantly increased due to its high consumption over the last three decades (Muthayya et al., 2014). Currently, rice occupies more than 150 million hectares globally (Fahad et al., 2019; Oo et al., 2022). Out of which Asia accounts for more than 140 million ha representing about 90% of the cultivated area (Maraseni et al., 2018; FAOSTAT, 2021) while Africa and South America contribute about 5.5 % (Balasubramanian et al., 2007). In terms of output, Asia is also the leading rice producer (677 million tonnes) followed by Africa and South America at 38 and 25 million tonnes respectively (FAOSTAT, 2021 ; Rao et al., 2017). In Africa, rice production has seen a consistent increase over the years (Mishra et al., 2022). West Africa is the continent's leading producer, accounting for more than 40% of the continent's total output (Ricepedia.org, 2021; Niang et al., 2017). However, despite this growth, revolutionary trend in preference of rice over other coarse grains among the population has resulted in rice demand consistently exceeding local production (Lançon and Benz, 2007; Kathiresan et al., 2020; Senthilkumar et al., 2021; Rodenburg and Saito, 2022). Thus rice importation has been adopted to fill the demand gap (Rodenburg and Saito, 2022; Saito et al., 2019). Considering the projected significant increase in West African population by 2050 (United Nations, 2019); further increase in rice demand is inevitable.

Consequently, rice production must rise geometrically either through intensification or expansion to meet this need. However, increase in rice production poses significant environmental threats due to the peculiar nature of rice ecosystem and inputs requirements. Rice is typically grown in a waterlogged environment. More than 70% of world's rice are produced under flooded condition (Maraseni et al., 2018; Malyan et al., 2016; Nawaz et al., 2022). Such anaerobic environment provides good condition for the methanogenic production of CH_4 (Ali et al., 2019; Reeburgh, 2003; Butterbach-Bahl et al., 1997; US-EPA, 2019; Conrad, 2007) and microbial reduction of NH_4^+ to N_2O (Matoso et al., 2019; Kögel-knabner et al., 2010). Similarly, through adaptation mechanism to the waterlogged condition in paddy field, rice plants have developed a special tissue that facilitates the transportation of both CH_4 and O_2 in and out of the root zone (Iqbal et al., 2020; Feng et al., 2021). This system is responsible for more than 80% of CH_4 emitted from paddy field (Iqbal et al., 2020). Additionally, provision of organic matter for conversion into CH_4 at early growth stage and release of CH_4 during photosynthesis at mid-growth stage (Conrad, 2007) are other important pathways through which rice production contribute to GHGs emissions. According to Allen et al. (2020), rice related activities especially at the low land areas are linked to large emissions of CH_4 and N_2O. Thus, rice production is an important source of both N_2O and CH_4 that affect global warming (Li et al., 2015; IPCC, 2014). Furthermore, CH_4 and N_2O from rice production have been projected to increase to about 4% by 2030 (US-EPA, 2019) due to population-induced increase in rice demand which raises fear on the sustainability of rice production techniques.

Currently, paddy rice production accounts for more than 10% of the total agricultural greenhouse gases emission (Allen et al., 2020; FAO, 2016) and is expected to rise as food demand increases. Already, global demand for food is driving high application of nitrogen fertilizer to agricultural ecosystems to a record-high (Wang et al., 2021) and has resulted in increase in the atmospheric content of N_2O. Therefore, any further increase in N-fertilizer application due to increased production means proportionate increase in N_2O emission (van Groenigen et al., 2010) which implies danger for the environment. The application of N-fertilizer does not just impact N_2O emission but it is also critical to CH_4 production in paddy rice system, although the nature of this relationship is still unclear. For instance, Shang et al., (2011) reported that the application of fertilizer to paddy rice caused a significant increase in CH_4 emission. But on the other hand, Dong et al. (2011), found more than 50% decrease in CH_4 emissions following fertiliser application. These contradictions suggest that an optimal N rate exists for the reduction of CH_4 emission from N fertilised rice field. Similarly, Yuan et al. (2019) revealed that fertilization had no significant effect on CH_4 emission but significantly increased CO_2 emission through increase in autotrophic respiration. From the above evidences, it is obvious that strategies to increase food production must be planned in the context of environmental and socio-economic sustainability (Silva et al., 2022). Consequently, biochar has been touted as a sustainable strategy for sustainable rice intensification.

Biochar is a carbonaceous, porous and amorphous material derived from the carbonization of biological residue (Hassan et al., 2020) under no or limited oxygen supply (Guo et al., 2020), and applied to the soil with the intention of improving soil productivity as well as sequestering carbon (Campos et al., 2020; Woolf et al., 2010; Maguyon-Detras et al., 2020). It is believed to possess the potential for mitigating agricultural greenhouse gas (GHGs) emission and improving the overall soil productivity (Agegnehu et al., 2017; Lehmann et al., 2011; Awad et al., 2018). Biochar acts as nutrient holder for plants and as well contains recalcitrant carbon. According to Woolf et al. (2010), about 12% of the current anthropogenic CO_2-C equivalent net annual emissions of CO_2, N_2O, CH_4 could be reduced without reduction in food security or endangering habitat or soil conservation by global implementation of sustainable biochar programme in agriculture. However, despite the promising benefits of biochar application, results of biochar effects on crop yield and GHGs emission have shown inconsistencies and the understanding of the underlying mechanism of its effect vague.

In particular is biochar and the mechanism of biochar effect on CH_4 emission under paddy system of rice production. Results of the responses of CH_4 emissions to biochar application under paddy condition are making the understanding of the underlying mechanism challenging (Feng et al., 2012; Nan et al., 2021). For instance, in their study, Knoblauch et al., (2011) reported a non-significant difference in CH_4 emissions between a biochar amended plot and the control after one year. But on the other hand, Qi et al. (2020) found a 2.64 increase in cumulative CH_4 emission from paddy soils amended with biochar than those without biochar. Increase in CH_4 uptakes after biochar applications have also been reported by different researchers (Nan et al., 2020a; Dong et al., 2013; Nan et al., 2020b) and this have been attributed to the inhibitory effects of biochar to CO_2 and N_2O emissions (Awad et al., 2018). Also, incorporation of biochar to pasture soil that contained ruminant urine caused a decrease of N_2O by as high as up to 70% (Taghizadeh-Toosi et al., 2011), which further underscores the inherent potentials of biochar in mitigating GHGs emissions from agriculture. Similar results have equally been reported (Wang et al., 2011; Awad et al., 2018), who observed that addition of biochar significantly lowered N_2O emissions from agricultural soils and was attributed to increase in adsorptive capacity of biochar due to enhanced oxidative reaction on the surface of the biochar as it ages (Singh et al., 2010). Furthermore, the effects of biochar on CO_2 emission have also differed. While Wang et al. (2011) reported zero effect of biochar application on CO_2 emission, Romero et al., (2021) found a significantly enhanced emission of CO_2. Emission of CO_2 decreased and increased with incubation time and temperature respectively (Case et al., 2012). The respective decrease and increase observed with time and temperature after biochar application is believed to be due to the reduction of the amount of available labile C in the biochar as it ages and increase in the microbial respiration rate (Case et al., 2012).

From the foregoing, it is obvious that there is no consensus on the effect of biochar amendment on GHGs emissions from paddy soils under rice cultivation. Therefore, further studies on the co-application of biochar and N-fertiliser are necessary to understand the impact of combined application of biochar and N-fertilizer on greenhouse gases emissions and yield of paddy rice under zero tillage especially in the African context. This is particularly important as emissions of GHGs are known to show significant variations depending on the properties of soil on which the biochar is applied Walkiewicz et al. (2020).

1.1. Statement of Research Problem

Emissions of greenhouse gases (GHGs) such as methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases are responsible for global warming (Zhang *et al.*, 2014). Paddy rice cultivation is an important source of CH_4 (Liu, et al., 2019) and N_2O (Zhang et al., 2018). It accounts for about 10% of the global agricultural GHGs emission (Maraseni et al., 2018) and have been projected to rise in rice production occasioned by population growth (Ullah et al., 2018). Therefore, alternative approaches to rice cultivation with concomitant advantage of raising crop yield and reducing emission footprint from paddy rice production are urgently needed.

Different strategies such as nutrient management, cultural practices, new rice cultivars and water management have been proposed (Liu, et al., 2019). However, none of these strategies have achieved the desired results of simultaneously reducing emission and enhancing rice yield. For instance, changing irrigation regimes and rice variety have been proposed but this combination results in either yield decrease or trade-off between CH_4 and N_2O (Feng et al., 2021). Similarly, some researchers have recommended the use of biochar (Xu et al., 2022; Li et al., 2022). But its effects have also resulted in either reduction of methane emission and increase in CO_2 and N_2O emission or vice versa or other forms of inconsistencies (Shin et al., 2021; Wang et al., 2016; Thammasom et al., 2016). Additionally, no tillage is also being investigated as a possible option for the reduction of GHGs emission from agricultural field due to its conservative nature and GHGs emission reduction potential. However, like the case of biochar and other methods earlier proposed, findings from no tillage has also shown inconsistencies regarding emission reduction and hence need to be further researched (Shang et al., 2021; Shakoor et al., 2021; Pe et al., 2017).

Apart from the inconsistencies in the results of biochar researches, it is also important to note that the large application rate required for biochar to engineer concurrent positive changes in crop yield and emission reduction also poses a challenge to its easy adoption by farmers. Therefore, researches looking at a more suitable combination of biochar and other supplemental sources of nutrient such as conventional N-fertilizer which optimizes application rate, productivity and emission reduction are urgently needed in the context of climate change.

Furthermore, previous researchers have incorporated biochar below the soil surface after or during tillage. This practice does not just disturb the soil structure but also exposes the soil organic matter to decomposition which may lead to increased emission of greenhouse gases (Senbayram et al., 2019). Therefore, for our experiment, we decided to adopt surface application of biochar mixed with nitrogen fertilizer, or biochar activated with cow dung, biochar alone or nitrogen fertilizer in an untilled soil. This is to enable us to compare the result from these treatment combinations with results of our control (conventional rice practice of soil tillage and chemical fertiliser application). Although one may argue that the surface application of nitrogen fertilizer in an untilled soil may encourage nitrogen volatilization. However, soil tillage also destroys the soil structure, encourages further decomposition of organic matter and leaching of nitrogen as well as enhances the process of nitrification. Hence, the need to carry out this trial to investigate the impact of combined application of nitrogen fertilizer with biochar, or sole application of either biochar or nitrogen fertiliser or the application of biochar activated with cow dung in an untilled soil on rice yield and GHG emission.

Similarly, from our literature search, no work has been found that combined biochar application with N-fertilizer under zero tillage. Additionally, our interest in this research topic stems from limited research work in West Africa on GHGs emission as well as on the use of biochar for rice production. Most researches on GHGs emissions are from Asia (Shin et al., 2021; Qi et al., 2020; Nan et al., 2020), Europe (Pe et al., 2017; Walkiewicz et al., 2020), America (Pfeifer-Meister et al., 2018), East Africa (Fungo et al., 2017; Arias-Navarro et al., 2013) and just a few from West Africa (Dossou-Yovo et al., 2016; Thomas et al., 2019; Brümmer et al., 2009).

Therefore, researches looking at a more suitable combination of biochar and other supplemental sources of nutrients such as conventional N-fertilizer which optimizes application rates, productivity and emission reductions are urgently needed in the context of climate variability and change. This is important as stabilizing agricultural emission of greenhouse gases from cropland is considered a strategic component of climate change mitigation strategy (Lipper et al., 2014) and requires different approaches.

1.2. State of the knowledge

Agricultural use of nitrogen fertiliser and paddy rice fields are important sources of atmospheric CH_4 and N_2O (Gao and Serrenho, 2023; Liu et al., 2019; Peyron et al., 2016). Agricultural activities account for over 60% of the global N_2O emitted into the atmosphere (Wang et al., 2017; Islam et al., 2018) while 10% of the global CH_4 emission comes from paddy field (Yuan et al., 2018). Research evidences indicate that biochar application (Woolf et al., 2010), alternate wetting or intermittent irrigation (Haque et al., 2016; Islam et al., 2018) or application of nitrification inhibitor (Wang et al., 2017) can mitigate GHGs emissions, albeit with some controversies (Shen et al., 2014; Cao et al., 2021). Furthermore, most of the GHGs studies on rice fields using co-application of biochar and nitrogen fertiliser have been conducted in Asia (Yi et al., 2016; Wu et al., 2019; Koyama et al., 2015). Hence, it is important to evaluated the effects of these strategies in West African environment which has its peculiar characteristics. It is also worthy of note that in the currently available literature, despite the increasing labour shortages globally, none of these strategies have been examined in no-tillage system.

1.3. Objectives

1.3.1. Overall objective

The general objective of this study was to improve low land rice yield under zero tillage through biochar and nitrogen management strategies to mitigate greenhouse gases emissions.

1.3.2. Specific objectives

Specifically, the study intends to:

i. Determine the effects of biochar and N-fertilization on nitrous oxide (N_2O) and methane (CH_4) emissions from paddy rice;

ii. Determine the morphological and yield response of rice to combine biochar and N-fertilizer application;

iii. Explain the residual effects of biochar and N-fertilizer amendments on soil physicochemical properties;

1.4. Research questions and hypothesis

1.4.1. Research questions

To test these objectives, we set out the following research questions:

1. What are the effects of biochar and N-fertilisation on the temporal pattern and cumulative CH_4 and N_2O emissions?
2. How do rice growth and yield respond to the combined biochar and N-fertiliser application?
3. What are the short-term or residual impacts of biochar and N-fertilizer amendments on soil properties?

1.4.2. Hypotheses

Due to the large surface area of biochar and its liming potentials, we hypothesize that co-application of biochar and N-fertiliser under no tillage system of rice cultivation will : a) enhance CH_4 emission by improving rice growth and soil porosity; b) reduce N_2O emission at high biochar and low N rate by biochar adsorption of NH_4^+; c) increase rice yield through reduction in N volatilization and increase in synchrony between rice N demand and N availability due to biochar-induced NH_4^+ retention in the soil.

CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. Rice as Food Source

In terms of total output, rice has emerged as the second most cultivated cereal (Van Nguyen and Ferrero, 2006; Nils-Gerrit Wunsch, 2023) and third most cultivated crop in the world (Nils-Gerrit Wunsch, 2023). Rice occupies about 11% of the world's arable land (Maraseni et al., 2018). It is grown in different regions of the world (Rodenburg and Saito, 2022) and consumed extensively. In West Africa, rice is one of the most essential food commodities especially among the urban dwellers (Wachiye et al., 2021). Although a non-native food, rice is gradually replacing other traditional foods. Its preference as food in West Africa has driven up both production and consumption. The region currently accounts for most of the rice grown in Africa (Ibrahim et al., 2021; Niang et al., 2017). Nigeria, Mali, Senegal, Sierra Leon, Guinea and Cote d'Ivoire are the leading rice producers in West Africa (USDA, 2021). In these countries, rice also constitutes an important part of daily diets particularly during the festive seasons.

Currently, rice demand in West Africa stands at 6% which is higher than any other region of the world (Katic et al., 2013). Increasing demand for rice in West Africa is linked to increasing per capita income and population growth (Katic et al., 2013; Mendez del Villar and Lançon, 2015; Zenna et al., 2017). This demand has resulted in deficit between rice production and supply (Mishra et al., 2022; Saito et al., 2019). In the period between 1973 and 2000, rice production and demand grew disproportionately at 4.6% and 6% per annum respectively (Ricepedia.org, 2021). While in 2020, rice production and consumption were estimated at 20 million tons and 34 million tons respectively (FAOSTAT, 2021; USDA, 2021). This indicates an increasing deficit between production and demand. Currently, the rice demand gap stands at more than 14 million tons (USDA, 2021). This demand has been projected to increase in the near future. The increasing gap between rice demand and production can be attributed to the method adopted for increasing rice production in the region. Whereas in different parts of the globe, increase in rice production has been achieved through intensification and use of machineries, in West African, ineffective area expansion has been the target for achieving increase in rice yield (Mendez del Villar and Lançon, 2015). Considering the inelastic nature of land and the poor nutrient status of soils in West Africa, rice intensification by area expansion is unlikely to provide the needed increase in rice output to match demand. Another point hindering yield increase in West Africa is the poor agricultural inputs by farmers in the region (Katic et al., 2013) which have culminated to rice yield deficit. This low yield has left many West African countries hugely dependent on Asia for meeting her rice need. Each year, more than 8 million tons of rice are imported into West Africa (Soullier et al., 2020), mainly from Vietnam, Thailand, India, China and Pakistan (Kathiresan et al., 2020).

Although rice importation has helped alleviate acute hunger and malnutrition in the region, its impacts on the economies of West African country are hugely damaging. It is therefore expedient that conscious efforts are made in order to increase rice sufficiency within the sub-region.

2.2. Rice production systems

Rice is a hydrophytic plant, and grows in diverse ecosystems (Rodenburg and Saito, 2022; Nawaz et al., 2022) and agroecological zones (Longtau, 2003). The quest to increase rice production due to increasing demand is driving the expansion of rice growing ecosystems and cultivation methods. Consequently, ecosystems which were hitherto considered unsuitable for rice production are now being harnessed to shore up production. Each of these ecosystems or methods possesses unique characteristics and potentials and have been classified using different criteria (Malyan et al., 2016; Nawaz et al., 2022; Rodenburg and Saito 2022). Some of the major classification criteria include: growing environment, method of establishment and tillage, etc... However, for the purpose of this review, only classification of rice production system based on growing environment, method of planting, and tillage were reviewed.

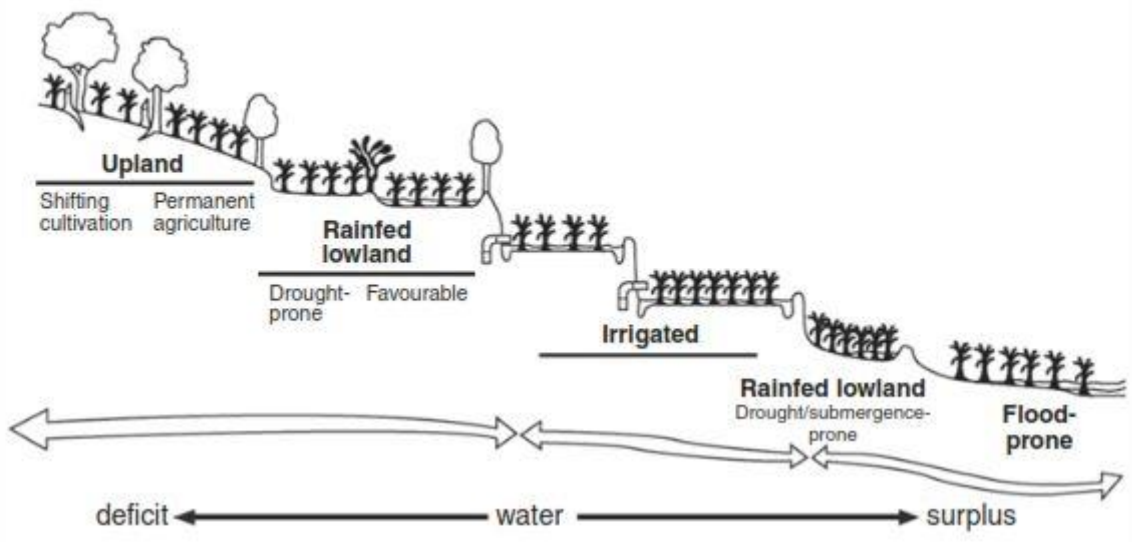
2.2.1. Rice production systems based on rice growing environments

Worldwide, rice production is supported by a variety of agro-ecosystems (Mishra et al., 2022). These ecosystems have been variously categorized by different authors using different criteria. According to Andriesse and Fresco, (1991) rice growing environments are broadly classified as upland (or aerobic) system and the low land (or wetland or paddy). The upland system is located at higher elevation and low soil moisture content except during the rainy season while the low land is flooded for most part of the season and located in lower elevations. On the other hand, Rao et al. (2017) identified two rice production system based on altitude and water source. Based on altitude rice production system include: upland, lowland and deep water based on altitude, while based water source, rice production systems are irrigated and rainfed based (Rao et al., 2017). Similar classification has also been adopted by Rodenburg and Saito (2022) who delineated rice growing environments based on management and soil hydrology as: irrigated low lands, rain-fed low lands and rainfed uplands.

Irrigated low land ecosystem is the most widely used environment for rice production (Prasad et al. 2017; Maraseni et al., 2018). Globally, it occupies more than 90 million ha of land used for rice production (Rao et al., 2017) and supplies about 75% of the world rice (Prasad et al. 2017; Maraseni et al., 2018; Fahad et al., 2019). Under this environment, rice establishment is largely through transplanting (Rao et al., 2017) and water supply by artificial irrigation. As such, low yield due to inadequate water supply is rarely encountered and more than one rice production per year is possible (Niang et al., 2017). The main characteristic of irrigated low land is the inundation of the soil for most part of the year through either artificial irrigation or natural precipitation.

In contrast, rainfed low land as the name suggests, depends on natural precipitations (Fukai and Wade, 2021). Hence, rice production in this environment is annual with low yield (Mendez del Villar and Lançon, 2015; Fukai and Wade, 2021). The system is practiced essentially in all parts of Africa and some parts of South East Asia and South Asia (Rao et al., 2017). Rainfed lowland rice production system including flood prone system are carried out along the coastal areas and river deltas (Rao et al., 2017). These environments are popularly known as Fadama lands in Nigeria and have been targeted for rice intensification in West Africa. Both rainfed and irrigated low land system are responsible for more than 90% of the global rice output (GRiSP, 2013).

Similar to rainfed low land, rainfed upland system of rice production also relies on natural precipitation for rice production (Fukai and Wade, 2021). Except for the heavier soils under rained low lands, rainfed upland, shares vastly identical characteristics as rainfed low lands. This system of rice production is largely present among subsistent farmers in Africa, Central America and some parts of Asia (Rao et al., 2017). Rainfed upland environment covers about 13% of the world's rice land (Prasad et al., 2017) and feeds about 100 million people globally (Ricepedia.org, 2021). Upland environment is characterized by low-lying valleys, undulating and steep sloping land with high runoff, and lateral water movement (Figure 1) (Prasad et al., 2017). The environment is heterogeneous, with variation not just limited to topography but also to the climate, and fertility status (Ricepedia.org, 2021). Rice cultivation in this environment is mostly annual through transplanting, wet or dry direct seeding (Rao et al., 2017) and depends largely on rainfall (Fukai and Wade, 2021). This is in contrast to the irrigated rice ecosystems, which has enough water to support one or more rice production per year. In general, the contribution of rainfed system to global rice output is about 19% (GRiSP, 2013) which is insignificant compared to the 75% contribution by lowland irrigated system (Bouman et al., 2007). Therefore, if rainfed system is expected to contribute significantly in combatting global hunger, production system needs to be improved by adopting better technologies and breeding for rice variety more adaptable to this system.



Upland	Rainfed lowland	Irrigated	Flood-prone
Level to steeply sloping fields; rarely flooded, aerobic soil; rice direct seeded on plowed dry soil or dibbled in wet, non-puddled soil	Level to slightly sloping, bunded fields; non-continuous flooding of variable depth and duration; submergence not exceeding 50 cm for more than 10 consecutive days; rice transplanted in puddle soil or direct seeded on puddle or plowed dry soil; alternating aerobic to anaerobic soil of variable frequency and duration	Leveled, bunded fields with water control; rice transplanted or direct seeded in puddle soil; shallow flooded with anaerobic soil during crop growth	Level to slightly sloping or depressed fields; more than 10 consecutive days of medium to very deep flooding (50 to more than 300 cm) during crop growth; rice transplanted in puddle soil or direct seeded on plowed dry soil; aerobic or anaerobic soil; soil salinity or toxicity in tidal areas

Figure 1: Rice growing environments (Prasad et al., 2017)

The situation is even more urgent and compelling in West Africa where upland rice covers 44% of the total rice land area, followed by rainfed low land at 31% while due to low irrigation facilities, irrigated rice system occupies just 12%, and the remaining percent is covered by mangrove rice (Saito et al., 2013; Sie et al., 2012). It is also important to note that most farmers in West Africa depend on rainfall for crop production, and with the erratic nature of rainfall most times, crop yield is low and extremely unpredictable. Apart from lack of irrigation, low inputs have also constrained crop production within the region (Katic et al., 2013; Zenna et al., 2017) (Table 1). Hence, it is obvious that in order to attain rice sufficiency and combat food insecurity in Africa, an improved facility and rice cropping system must be adopted.

Table 1: constraints to rice production under different rice growing environments in Africa and their yield potentials

Production environments	% contribution to production area	Potential/actual yield (ton/ha)	Limiting factor		
			Abiotic factors	Biotic factors	Input use
Rainfed upland	30	2-5/1.2	P and N deficiencies, acidity, Al toxicity, moisture stress, poor nutrient status of soil, erosion	Weeds, termites, stem borers, disease, birds, nematodes and rodents	Very low
Rainfed lowland	33	3-6/1.9	Iron toxicity, N and P deficiency, water management	Weeds, termites, stem borers, Diseases birds	low
Irrigated	26	5–12/1.9–3.7	N deficiency, salinity and alkalinity, extreme temperatures	Weeds, stem borers, birds	low
Mangroove and swamp	4	2–4/<1	Acid sulfate, salinity, Fe toxicity, excess water	Insect pests, diseases, birds	Very low

Source: Zenna et al. (2017)

2.2.1.1. Rice growing environments and GHGs emissions

The contrasting moisture conditions of rice growing environments create varying gas dynamics between these systems. In upland environment for example, the soil is mostly dry and respiration is therefore aerobic and as such can contribute to the emission of both CO_2 and N_2O emissions (Phapumma et al., 2020). While under wetland or low land, the soil is mostly submerged with limited supply of oxygen which encourages anaerobic respiration. This anaerobic condition is important in greenhouse gases emission particularly, methane which is crucial in the atmospheric chemistry and global warming (Hasan, 2014; Reeburgh, 2003). Most of the emitted methane from anaerobic environment such as rice paddy into the atmosphere are principally produced as an end product of methanogenic degradation of organic matter by micro-organisms (Butterbach-Bahl et al., 1997; US-EPA, 2019; Conrad, 2007). The presence of organic matter and flooding in rice field enhances and sustains CH_4 emission. Flooding also plays a key role in the cycling of N and C in the soil which can trigger the emission of N_2O (Shaaban et al., 2022). In re-emphasizing the role of flooding in GHG emissions, Chidthaisong et al. (2018) demonstrated that continuously leaving rice field in flooded condition significantly enhances the evolution of GHG into the atmosphere. While the high N accumulation in irrigated rice systems provides N substrates required for the emission of both CH_4 and N_2O (Bouman et al., 2007). Hence, mitigating GHG emission from rice field requires adjustment in rice management practices.

2.2.2. Rice production system based on rice establishment method

Using the method of establishment to classify rice production system, two main methods can be distinguished, and they include transplanting and direct seeding method (Mishra et al., 2017). Over the years, these two methods have emerged as the most popular system of rice establishment methods in the world. They have also attracted lots of focus on ways to make them more efficient and profitable.

2.2.2.1. Direct seeding

Direct seeding involves rice establishment by sowing or broadcasting of rice seeds into the field rather than through seedlings from nursery (Farooq et al., 2011). Direct seeding is one of the oldest systems of rice establishment method especially in developing countries (Nagargade et al., 2018). Currently, about 23% of global rice fields are established through direct seeding method (Nagargade et al., 2018) which exists in various forms. The choice of which type of direct seeding methods to use depends on the edaphic and climatic condition of the location as well as the economic status of the farmer. But generally, three methods of direct seeding have been established (Rao et al., 2017) and include: dry-seeded, wet-seeded, and water-seeded, rice establishment method.

2.2.2.1.1. Dry-seeded rice

In this method, dry rice seeds are broadcast, drilled or dibbled directly in a dry un-puddled fields (Ishfaq et al., 2020; Yadav, 2011; Alam et al., 2020) using either heavy machineries or simple tools. The technique is practiced mainly in rainfed upland and low land fields (Chen et al., 2018) and accounts for about 20 million ha of rice field globally (Chen et al., 2018). Dry rice seeding method is majorly practiced where facilities exist for precise water control (Farooq et al., 2011).

2.2.2.1.2. Wet-seeded rice

Contrary to dry seeding, in wet seeding, the soil is puddled either mechanically or manually to achieve similar soil condition as soil under transplanting method before being seeded with dry or pre-germinated rice seeds (Yadav, 2011; Alam et al., 2020). The seeding method could be through broadcasting, dibbling or drilling using either mechanical planter or dibbling sticks (Rao et al., 2017). This method differs from dry-seeding and wet-seeding by tillage. In wet-seeding, the field is puddled or tilled under wet condition before seeding while there is no tillage in dry-seeding

2.2.2.1.3. Water-seeded rice

When dry or pre-germinated rice seeds are broadcast on submerged rice field as a way of establishing rice production, such method is referred to as water-seeding (Bista, 2018; Farooq et al., 2011). This method is popular where weed or weedy rice is a serious constraint to rice production, and are among the commonest rice establishment methods in certain parts of America, Australia and Europe (Kumar and Ladha, 2011). This technique is used for rice establishment under irrigated low land with level or non-undulating topography (Rao et al., 2017).

Each establishment method is unique in terms of benefits and limitations. In their studies, Mishra et al. (2021), Ishfaq et al. (2020), Prasad et al. (2020) have all reported that the use of direct seeding method of rice establishment is more profitable to farmers, and ensures better environmental protection than the traditional puddle transplanting system. The non-puddling system as obtained in direct seeding system conserves and sequesters carbon into the sub-soil (Zhang et al., 2015). A cost-benefit analysis of transplanting and direct seeding methods has equally confirmed the profitability of direct seeding over transplanting method (Singh et al., 2020). Nevertheless, there are also some challenges associated with direct seeding. Some of these challenges such as deficiencies of some micro-nutrients such as zinc and iron (Bista, 2018; Joshi et al., 2013) and weed competition (Matloob et al., 2014; Bista, 2018; Farooq et al., 2011) can result in low yields. But overall, direct seeding is still hugely encouraged due to reduced financial and environmental costs associated (Devkota et al., 2020). Also, with sustainability on the forefront of the global agenda, direct seeding method seems a viable option for rice intensification. It is therefore expedient that more experimental trials be conducted in different rice growing environments as well as regions to quantify the extent of benefits derivable by switching from traditional transplanting method to direct seeding method.

2.2.2.2. Transplanting method

In different parts of the world, rice is commonly grown through transplanting (Rao et al., 2017). The system involves raising rice seedlings in a nursery until they are about 20-30 days old (Figure 2) before being transplanted into a wet-puddled (Rao et al., 2017) or non-puddle paddy field either manually or mechanically (Nawaz et al., 2022). The manual system is the most widely used system of rice transplanting (Nawaz et al., 2022) especially in developing countries where labour is relatively cheap and available for such operations. Also, the low popularity of machine transplanting of rice in West Africa for instance may be related to inadequate capital and low level of technology in agriculture in the region. This is in contrast to advanced countries like Japan and Korea where rice transplanting using machines is a common practice and have been so for many years (Sudhir-Yadav et al., 2014). In these countries and method, seedlings are raised on a polythene sheet, spread with a mixture of soil and farm yard manure which are subsequently transplanted with machine into the field (Rao et al., 2017). Transplanting especially with machines reduces drudgery associated with farming. It is also credited with a yield increase of about 1.57 ton ha^{-1} over direct seeding (Devkota et al., 2020). Additionally, machine transplanting maximizes labour and increases profit return, nutrient use efficiency as well as water productivity over manual or hand transplanting (Prasad et al., 2020). However, regardless of whether manual or machine system, transplanting generally requires high water inputs, labour and machinery for puddling, as such the profitability and sustainability of transplanting system has come under scrutiny (Ishfaq et al., 2020). The system is also blamed for the destruction of soil structure, decreases in land and water availability and productivity (Alam et al., 2020) and a significant contributor to the emission of greenhouse gases.

Surprisingly, despite the reported challenges inherent in transplanting method of rice establishment, the method is still popular among many farmers in different parts of the world especially in Africa. The reason is yet to be fully documented; however, culture as well as its old age may not be ruled out. Additionally, the poor adoption of direct seeding over transplanting method may also be related to inadequate extension services. Lack of information on the benefits of direct seeding method to farmers may lead to low adoption of the system. Therefore, there is need to increase extension efforts communicating the associated benefits of direct seeding over transplanting method to farmers.

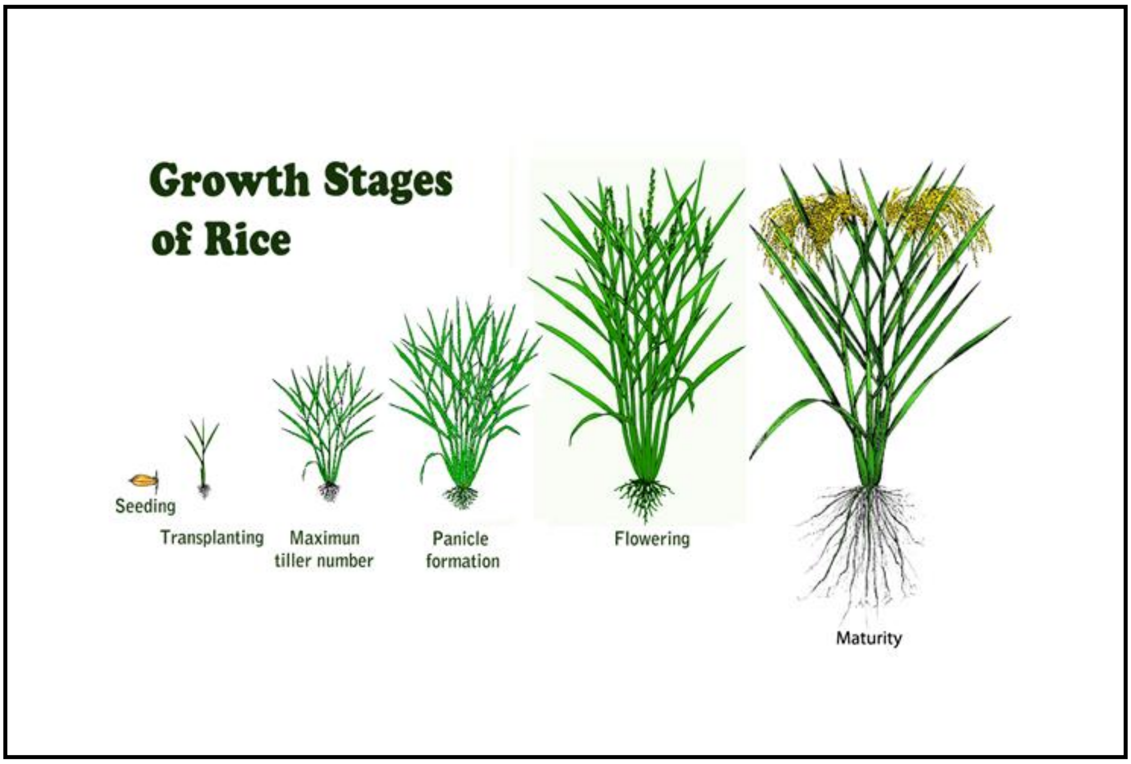


Figure 2: Rice developmental stages (Nelson et al., 2014)

2.2.2.3. Rice establishment methods and greenhouse gas emission

Rice establishment methods contribute significantly to GHG emissions from rice field. The total GHG budget from rice production is an accumulation of all emissions from soil preparation before rice establishment to rice harvesting. These activities leading to rice establishment differ between rice establishment methods and hence their impact on GHG emissions also varies. For instance, the dry soil and non-puddling system as practiced under dry-seeding system of rice establishment offers minimum disturbance to soil surface and as such play considerable role in GHG reduction (Kraehmer et al., 2017) particularly, methane. Whereas, puddling activities and high water as obtain in transplanting system promotes methane emission (Kumawat et al., 2019). Similarly, soil pulverization in transplanting also exposes soil carbon as well as soil N pools to oxidation which can lead to increase in GHG emissions. Since emission increases as rice growth increases and peaks at flowering stage (Ma et al., 2014), varied response of rice to establishment methods is expected and can significantly affect emissions. Estimates suggest that about a quarter of the current emission of greenhouse gases (Alam et al., 2020) and 50% of the current water demand can be cut by implementing direct seeding non-puddle system of rice production (Priyanka and Ekta, 2013; Mishra et al., 2021). More than 30% increase in CH_4 emission in puddled transplanted system compared to direct seeding has also been reported (Mohanty et al.,2017).

Furthermore, Alam et al. (2020) investigated the impact of rice establishment techniques on soil properties, greenhouse gases and rice yield and found that replacing transplanting by direct seeding can cut global warming potential by more than 25% while sequestering about 79% organic carbon into the soil. The reduction in GHG emission in direct seeded rice field is linked to slow root development and aerobic condition of direct seeded rice field (Mohanty et al., 2017; Pittelkow et al., 2014). Conversely, this aerobic condition favours the nitrification process and hence promotes the emission of N_2O which is suppressed under flooded condition (Mohanty et al., 2017).

On the other hand, the amount of GHG abated using direct seeding is not homogenous among the various direct seeding methods. A more significant reduction in dry-direct seeded rice compared to wet-seeded direct planting has been reported (Kumar and Ladha, 2011). According to Kumar and Ladha (2011) under dry-direct seeded, reduction in GHG emission can reach as high as between 24% to 79%, while it is between 8% to 22% in wet-seeded rice systems, compared to puddled transplanted system (Kumar and Ladha, 2011).

2.3. Sources and nutrient requirements for rice production

Nutrient application to crops including rice is essential for achieving optimum yield and reducing nutrient deficiency and disease attack. These nutrients sources are broadly referred to as fertilisers (organic and inorganic) and are important for crop production. While the inorganic fertilisers are of synthetic origins, organic fertilisers are of biological origin. The high precision of inorganic fertilisers makes it a preferred choice among farmers including rice farmers. In total, about sixteen nutrient elements essential for crop growth exists (Food and Agricultural Organization (FAO), 2000). Out of which, three (Nitrogen, Phosphorus and Potassium) are the most limiting for rice production (Shahena et al., 2021) and are mainly derived from air and soil (FAO, 2000) and stored as inorganic fertilisers. These inorganic fertilisers are subsequently used to replenish the nutrient status of degraded soil for crop utilisation. Particularly, come in handy where crop performances especially rice are deficient due to seasonal variabilities, or heterogeneity of rice growing environments with respect to soil properties and topographic positions (Wade et al., 1999). Consequently, fertiliser application to crop production has been on the increase and has been playing a critical role in increasing crop yield since early 90s. The green revolution in agriculture in the early 90s were partly credited to the agricultural use of nitrogen fertiliser (Maraseni et al., 2018) in the world.

2.3.1 Nitrogen

2.3.1.1 Nitrogen fertiliser for rice production

Nitrogen is one of the most important elements for crop production. Its presence in the soil is crucial in promoting crop production and mitigating global food shortage. Two main sources of nitrogen for plants have been identified: natural sources or artificial supply by man (Figure 3). The natural sources are through lightning and fixation by microorganisms (Shah et al., 2020), while the artificial source involves the direct application of industrial nitrogen by man. The global nitrogen fixation is estimated at about 270 billion N per year. Out of which, 85% is fixed by soil micro-organisms while 15% are derived from industrial processes (Igboji, 2020). Consequently, more than half of the global population depend on nitrogen induced crop yield for their survival (Shah et al., 2020). The only other nutrients that come close to nitrogen in terms of importance are phosphorus and potassium (Rao et al., 2017). Although N is applied at a significantly higher amount compared to phosphorus and potassium (Rao et al., 2017).

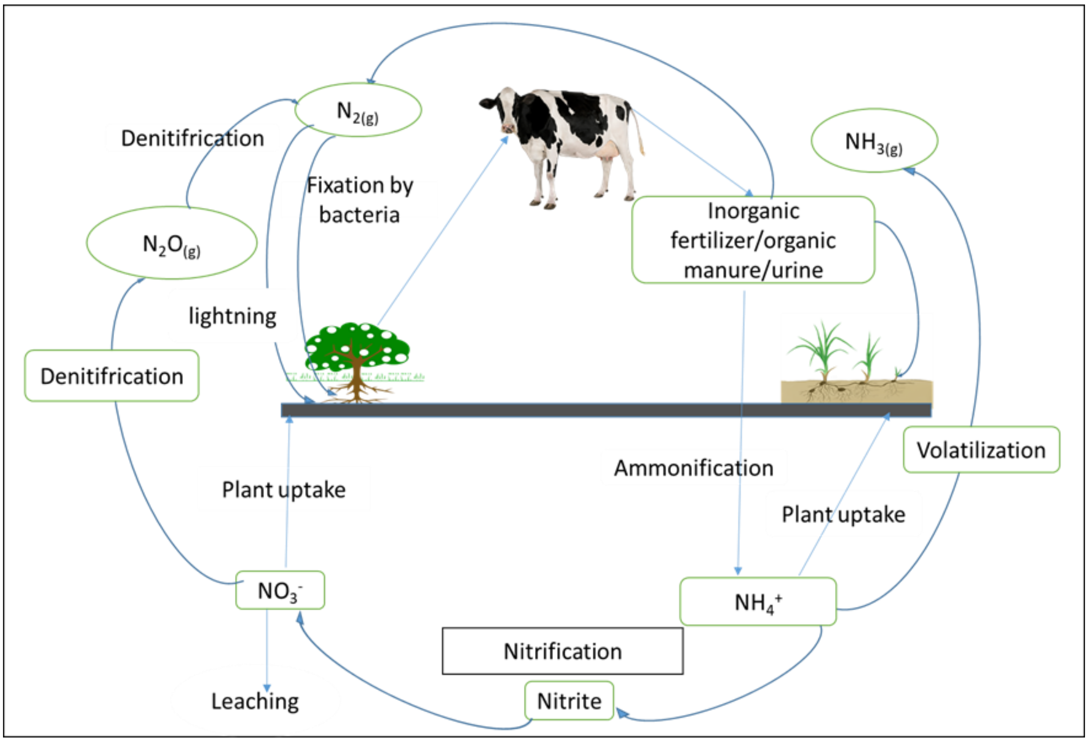


Figure 3: Nitrogen cycle (Ramya et al., 2016)

2.3.1.2. Effect of nitrogen application and rice production on greenhouse gases emissions

Modern agriculture relies heavily on nitrogen (N) application for maintaining and/or increasing crop yield (Gu and Yang, 2022). The high demand for food is driving the increased use of urea and other nitrogen-based fertilizers particularly, for rice production (Prasad et al., 2017). However, most of the applied N fertilisers are lost to the environment as nitrate, ammonia or nitrous oxide (N_2O) (Gu and Yang, 2022; Prasad et al., 2017; Cayuela et al., 2014; Lorenz and Lal., 2018a; Wang et al., 2021). The non-synchrony of N application and demand by plants leaves large amount of the applied fertilizer unutilized (Wang et al., 2021). Excess nitrogen fertiliser use can also hamper rice performance through soil acidification and salinization (Xia et al., 2020) and cause direct emission of N_2O (Kim et al., 2013). Nitrous oxide (N_2O) is an important GHG with 298 more warming potential than CO_2. Apart from serving as a direct source for N_2O, the improved rice growth from N application to rice field also favours the development of rice aerenchyma tissues which ultimately enhances the transportation of not just CH_4 but also N_2O into the atmosphere (Conrad, 1993; Rao et al., 2017). The provision of substrates for methanogenic production of CH_4 from the root zone (Ashitha et al., 2021) has also been linked to nitrogen fertiliser use. Challenges associated with nitrogen fertiliser are also linked to the nitrogen fertiliser source. For instance, (Hasan, 2014) demonstrated that switching from urea as nitrogen source to ammonium sulphate could be beneficial in reducing CH_4 associated with nitrogen application.

The growing rice demand is expected to exacerbate GHGs emissions from rice field especially in Africa where fertiliser management is poor. Currently, Africa accounts for about 4.5% of the global methane emission from paddy rice production (FAOSTAT, 2021). But the future rice demand is expected to enhance methane emission to about 6.1% and 7.6% of the current rate by 2030 and 2050, respectively (FAOSTAT, 2021). Hence there is need to develop strategies that ensure reduction in the N dependence (Prasad et al., 2017), as well as increase N use efficiency. In this context, biochar addition can be beneficial (Cai and Chang, 2016). Studies suggest that biochar is efficient in immobilization of pollutants (Jeffery et al., 2013), increase in N retention as well as reduction in N leaching (Wei et al., 2019; Güereña et al., 2013; Mukherjee et al., 2014). It is therefore important that efforts aimed at increasing food production by increasing nitrogen fertiliser application should be planned bearing in mind the challenges associated with its use.

Contrary to the trend of inorganic fertiliser use in agriculture and rice production, the use of organic fertiliser has been on the decline since the invention of inorganic fertiliser. The bulky nature as well as the large amount required of it in order to meet crop nutrient requirements are some of the factors limiting the large-scale deployment of organic fertiliser especially among commercial farmers. However, in recent times, interests in the use of organic fertiliser have rekindled due to the need to protect human health and the environment. This new interest in the use of organic fertiliser has consequently birthed new technologies for combatting some of the previous challenges hindering the use of organic fertiliser. One of such technologies is biochar.

2.3.2. Biochar

The term biochar describes carbon rich materials primarily used for soil improvement with the potential to sequester carbon in the soil (Sohi *et al*., 2010; Brantley *et al.* 2015). It is a solid by-product of carbonisation of biomass under high temperatures of above 300 ^{0}C and low to zero oxygen supply (Ralebitso-Senior and Orr, 2016). It also represents any biomass which has been thermodynamically modified and which contains an oxygen to carbon ratio of less than 0.6 (Brockamp and Weyers, 2021).

Although the concept of biochar dates back thousands of years ago, and can be traced to the Indian settlement sites in the Amazon (Lehmann *et al*., 2004), interest in its use for agriculture gained resonance among researchers recently. This interest among researchers originated from trying to understand the "dark amazon earth or "Terra Preta de indio" in Brazil (Brockamp and Weyers, 2021) which have been found to be dark and permanently fertile (Brewer et al., 2012). The high fertility of this soil has provided the basis for further research into and for the development of biochar. Some researchers believe that understanding this soil could offer a solution to the management of the highly degraded tropical soils and ecosystem (Schmidt, 2013).

2.3.2.1. Sources of feedstocks for biochar production

Technically speaking, any material of carbonaceous origin can be a source of biochar. Materials such as municipal wastes, used tires, old building materials as well as forestry residues are all potential candidates for biochar production (Brewer and Brown, 2012). The harnessing of these materials for biochar production and use have been encouraged as part of the ongoing campaign to minimize waste, improve soil fertility, decontaminate and mitigate greenhouse gases emissions (Domingues et al., 2017) especially from agricultural production systems. But despite the availability of these materials, in reality, the production and utilization of biochar in agriculture is still largely limited. These limitations are drawn from factors such as feedstock material safety and availability, market conditions for biochar and its process co-products, local soil properties, and the combined environmental impacts (Brewer and Brown, 2012). Consequently, only woody biomass is recognized as the most important materials for biochar/charcoal production globally (Suliman et al., 2016). According to Domingues et al., (2017), some of the factors which favour the use of wood and sugarcane for biochar/charcoal production includes its higher aromatic character, carbon concentration, low hydrogen to carbon ratio (H/C) as well as its Fourier Transform Infrared Spectroscopy (FTIR) spectra features.

2.3.2.2. Biochar production techniques and characterisation

The diverse need and wide application of biochar have formed the basis of biochar production techniques. This is so because different production techniques, processes and feedstock employed during biochar production determine the properties of the resultant biochar. The currently available biochar production techniques include: use of bubbling fluidized bed, paddle kiln, wagon reactors, thermochemical conversion and agitated sand rotating kiln

(Yaashikaa et al., 2020), gasification, pyrolysis, combustion, liquefaction, hydrothermal carbonization, and torrefaction (Xiong et al., 2017; Brewer and Brown, 2012; Pang, 2019; Chi et al., 2020; Yaashikaa et al., 2020a; Bridgwater, 2011). However, the most popular methods are pyrolysis (i.e., thermal decomposition of biomass under high temperature and low or no oxygen supply); gasification (i.e., thermal decomposition of biomass into gas and traces of hydrocarbons); torrefaction (mild pyrolysis under lower temperature of about 300^0C), thermochemical conversion, and hydrothermal carbonization (thermal decomposition of wet biomass under low temperature of about 280^0C) (Yaashikaa et al., 2020). Each of these techniques yields varying types and amounts of biochar. For example, pyrolysis of biomass yields bio-oil, biochar and syngas (Sakulkit et al., 2020; Pang, 2019; Dahlquist, 2013) while gasification and hydrothermal carbonization produces hydrochar, and syngas and char respectively (Yaashikaa et al., 2020). Since the biochar physicochemical properties are related to the feedstock and production condition (Kookana et al., 2011; Hassan et al., 2020; Kumar et al., 2020), for maximum biochar output, the production technique chosen must be appropriate for the selected feedstock (Yaashikaa et al., 2020). Thus, Bhaskar and Pandey (2015) have recommended the use of thermochemical method for biochar production. This method is considered advantageous over other methods because of its relatively simple approach; does not require the separation of the different components of the biomass and as such, no pre-treatment is needed (Bhaskar and Pandey, 2015). Furthermore, the ease of the implementation of thermochemical method especially in developing countries and the faster economic returns also makes the method more attractive (Bhaskar and Pandey, 2015).

Similarly, in order to maximize biochar benefits, its properties must be determined before application. The process of determining biochar's properties is known as characterization or classification. The essence of which is to identify the biochar's agronomic and environmental benefits as well as elemental composition (Mukome and Parikh, 2016). Characterization can also be done to determine the ability of biochar to perform other functions such as removal of contaminants (Yaashikaa et al., 2020). Currently, the techniques used for biochar classification or characterization include X-ray diffraction (XRD), Scanning Electron Microscopy (SEM), Thermo-gravimetric Analysis (TGA), Brunauer-Emmet-Teller Analysis (BET), Nuclear Magnetic Resonance Spectroscopy (NMR), X-ray photon Spectroscopy, Raman Spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), Energy Dispersive Spectroscopy (EDS) (Yaashikaa et al. ,2020a; Lu et. ,2021; Stylianou et al.,2020). Each of these methods gives detailed information on the properties of any given biochar and are utilized for different purposes. SEM gives information about the surface structures of biochar while EDS provides details on biochar elemental composition. Furthermore, FTIR is used for determining the different functional groups present on the surface of a biochar, and XRD is for the determination of the structure and crystallinity of biochar. Similarly, TGA is for thermal analysis of both the chemical and physical features of biochar (Yaashikaa et al., 2020a; Lu et.,2021; Stylianou et al., 2020). It is worthy of note that sometimes, one of these methods is insufficient to give detailed information about a biochar and as such more than one method can be applied in combination.

Despite the availability of different instruments for biochar characterisation and analyses, challenges in biochar researches still exist. One of such challenges especially for biochar in the soil, lies on being able to distinguish biochar from soil organic matter and other particulate forms of carbon in bulk soil samples (Sohi et al., 2010). Also, the inherent physicochemical complexity and variability of biochar in the soil also constitute another challenge in isolating the individual properties of biochar (Bird et al. 2015; Deem et al.,2017). Additionally, the often-high dependence of biochar characteristics on numerous factors such as operating parameters, reaction residence time, pressure, highest treatment temperature (HTT), processing heating rate, reaction vessel (orientation, dimensions, stirring regime, catalysts, etc.), pre-treatment conditions as well as the flow rate of ancillary inputs are also sources of concern during biochar characterization (Lehmann and Joseph, 2009; Kumar et al., 2020).

2.3.2.3. Mechanisms of biochar’s influence on soil physical properties

Soil physical properties are important indicators of the general health and productivity of a soil. They are highly variable both in space and time and are strongly affected by management. They are also expressed using different indicators such as soil bulk density, soil porosity (macro and micro), aggregate stability, water holding capacity, hydraulic conductivity, particle sizes and particle density. These properties are affected differently when biochar is incorporated into the soil.

2.3.2.3.1. Soil bulk density

This is a soil physical property that is closely related to the cohesiveness and structure of soil (Zhang et al., 2021) and can be measured either as bulk density or particle density also known as skeletal or true density (Brewer and Brown, 2012). Soil bulk density is defined as the dry weight of soil over its bulk volume (Rahman et al., 2020) and is affected by biochar application to soil. The low density of biochar (typically between 0.05 and 0.57 kg m^{-3}) (Zhang et al., 2021) causes decrease of soil bulk density when biochar is added to soil. It is estimated that an extensive utilization of biochar can reduce soil bulk density to as much as up to 3-31% (Lorenz and Lal, 2018). Other researchers have also reported decreases in soil bulk densities following biochar application (Zhang et al. 2010; Calamai et al., 2019; de Jesus Duarte et al., 2019; Zhang et al., 2020). The mechanism involves alteration of soil aggregates and addition of soil organic matter (Jien and Wang, 2013), combination of low density of biochar with soil aggregates (Zhang et al., 2020) and increase in soil aeration due to biochar-induced increase in soil porosity. Contrastingly (Sandhu et al., 2017; Moragues-Saitua et al., 2017; Ghorbani et al., 2019) have reported non-significant impacts of biochar application on soil bulk density which was attributed to low biochar application rate (10 $tonha^{-1}$), suggesting that the magnitude of biochar influence on soil bulk density depends on biochar application rate (Yao et al., 2017).

2.3.2.3.2. Soil porosity and surface area

According to Rouquerol et al. (2014) soil pores are generally classified as micro-pores (pores with internal width >2nm), meso-pores (pores 2 ≥ 50nm), macro-pores (pores < 50nm), and nano-pores (approximately 100 nm). Irrespective of their sizes, soil pores are very important for soil productivity. This is because soil pores provide the necessary spaces and aeration for soil microbial community and transformation and storage of water (Zhang et al., 2021). Soil porosity is affected by biochar addition (Baiamonte et al., 2019). It is estimated that the application of biochar to soil could result in 14–64% increase in soil porosity (Lorenz and Lal, 2018). Biochar molecular structure changes soil porosity by altering the arrangements of both inter and intra-pores within the soil structure (He et al., 2021). Depending on biochar feedstock, biochar can also elicit increase in total as well as micro-porosity (Yang et al., 2021). Jien and Wang (2013) have reported about 50% increase in total porosity of biochar amended soil than the control. Apart from its direct effect on total porosity and surface area, biochar through its high total porosity can also retain water in all the pores, thus increasing the water holding capacity of the soil (Asai et al., 2009).

2.3.2.3.3. Aggregate stability

Soil aggregate stability is an important indicator of soil health and productivity. It determines air and water movement into and out of the soil. It is also an important indicator of soil erodibility status, and can either be measured though wet-sieving or drying sieving method

(Moragues-Saitua et al., 2017; Zhang et al., 2020). The wet-sieving approach is the most frequently used, and involves the separation of different sieve size fractions: macro-aggregates (> 2mm), macro-aggregates (2-0.5 mm), small macro-aggregates (0.5-0.25 mm), micro-aggregates (0.25-0.053) (Zhang et al., 2020).

The percentage stable aggregate (%SA) according to Hillel (2003) is calculated thus:

$$\%SA = 100x \frac{\text{retained weight} - \text{sand weight}}{\text{total sample weight} - \text{sand weight}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(equation 1)}$$

Different researchers have demonstrated that application of biochar significantly enhances soil aggregate stability (Zhang et al., 2020; Yang and Lu, 2021; Baiamonte et al., 2019). Biochar through its organic matter content affects soil aggregate stability in different ways (Rahman et al., 2020). Firstly, the organic matter content of biochar bonds with polyvalent cation in the soil and thus acts as binding agent for clay particles (Rahman et al., 2020). Secondly, the functional group of biochar can neutralize the negative charges on clay particles, thereby increasing intramolecular attraction which can bind and encapsulate clay particles and thus reduce hydrophobicity (Rahman et al., 2020). Decrease in hydrophobicity increases soil particle aggregation. It is estimated that under wet condition, biochar application can induce 3-226% increase in wet aggregate stability (Lorenz and Lal, 2018). Joseph et al. (2020) asserted that the application of biochar at 10, 20 and 30 $tonha^{-1}$ all significantly improved indicators of soil aggregate stability. Similar finding has also been reported by Yang and Lu (2021). It is important to emphasise that due to its time dependent nature, soil aggregate stability could vary from time to time which implies that knowing the state of aggregation of a soil at a particular time is insufficient to express the soil's true structural characteristics (Hillel, 2003).

2.3.2.3.1. Water holding capacity, hydraulic conductivity, and particle sizes

Hydraulic conductivity, water holding capacity, particle sizes and density are all parameters necessary for the description of water movement in the soil. These parameters are also closely related to each other and readily influenced by biochar. Through its effects on soil bulk density, structure and porosity, biochar by extension improves the water holding capacity of soils especially sandy soil. Its organic matter composition binds the soil particles together (Jien and Wang, 2013; Yang and Lu, 2021), thereby improving the soil's water retention capacity (Yang and Lu, 2021). It is reported that the application of biochar can induced 4-130% increase in soil available water, decrease and increase in hydraulic conductivity of coarse and fine textured soils respectively (Lorenz and Lal, 2018; Edeh et al., 2020). An estimate which totally agrees with the finding of Zhang et al. (2020) who reported 58% increase in saturated hydraulic conductivity due to biochar application. The general trend is that the capacity of biochar to improve soil water properties is related to the soil's particles and is more pronounced in coarse textured soils at high application rates of >30≤70 t ha^{-1} (Edeh et al., 2020).

The meso and micro-pores of biochar all play major roles in determining the resultant soil physical properties after biochar amendment (Yang et al., 2021). Yang and Lu (2021) revealed that the application of rice straw, maize straw, wheat straw, rice husk and bamboo biochars all significantly enhanced the available water content and significantly reduced the tensile strength and cohesion of the amended plots compared to the control. More than 60% increase in water retention capacity has been reported following biochar application (Jien, 2018). The redistribution of the proportion of soil aggregates and the formation of larger aggregates increases water movement within the soil (Jien and Wang, 2013). The dependence of hydraulic conductivity on soil particle sizes, clay content, organic matter and particle size distribution (Zhang et al., 2021) which are easily modified by biochar is responsible for the positive changes in soil water holding capacity and hydraulic conductivity following biochar addition. Biochar can also improve soil water properties by increasing soil organic matter and porosity as well as swelling effects of biochar leads to loading of water molecules on its surface (Teodoro et al., 2020). Using three land use types, Karim et al. (2020) established that biochar positively and significantly enhanced soil moisture in all the tested land use types. Addition of biochar prevents the sealing of soil surface and improved soil infiltration rate (Abrol et al., 2016). Biochar effects on soil water properties seem temporary. This was confirmed by Kalu et al. (2021) who showed that most of the improvements recorded in plant water availability during the initial years after biochar application faded with time due to dilution of biochar concentration in soil. Similarly, Moragues-Saitua et al. (2017) also reported a decrease in soil available water as well as hydraulic conductivity which was attributed to the clogging of the soil pore spaces after biochar addition.

2.3.2.4. Biochar application and soil chemical properties

Biochar impacts soil chemical properties, but the magnitude of impact varies according to biochar properties. The process of biochar production leads to large differences in biochar properties (Amonette and Joseph, 2009) and hence the variation of its impact on soil. Here, some of the most reported effects of biochar on soil chemical properties using some indicators, such as changes in soil pH (Liu et al., 2016; Laghari et al., 2015; Nguyen et al., 2021; Awad et al., 2018; Yu et al., 2021; Jeffery et al., 2017; Zhang et al., 2010; Bista et al., 2019; Mukome and Parikh, 2015; Mukome and Parikh, 2016; Zhang et al., 2021) were enumerated.

2.3.2.4.1. Soil pH

Soil pH ranks as the most widely reported indicator of the effect of biochar on soil chemical properties. This may be due to the interconnectivity of soil pH to other soil chemical processes especially nutrient availability to plants. According to Mukome and Parikh (2015) agronomic consideration of biochar is highly hinged on its influence on soil pH and is an essential chemical property of the soil which regulates nutrients availability and crop productivity. It also plays a significant role in regulating the solubility of heavy metals in the soil and its value for optimum crop performance ranges between 6.5 and 7.5 (Rahman et al., 2020). Most biochars are alkaline in nature with a pH >7 and their use often raises the pH of soil (Mukome and Parikh, 2015). Result from meta-analysis showed that application of biochar induced an overall increase of 11.5-11.9% in soils pH compared to untreated plots (Awad et al., 2018). Biochar pH is dependent on feedstock and pyrolysis temperature and increases with increasing pyrolysis temperature (Mukome and Parikh, 2015; Zhang et al., 2021). The factor responsible for the increase in biochar's pH as pyrolysis temperature increases is the increased rate of biomass conversion into ash: a known liming material. Also the basic functional groups in biochar which adsorb inorganic minerals and alkaline components during pyrolysis are affected by pyrolysis temperature and hence contributes to the high pH value of biochar and biochar amended soils (Zhang et al., 2021).

2.3.2.4.2. Soil cation exchange capacity (CEC)

Soil cation exchange capacity (CEC) is an inherent capacity of the soil, and reflects the percentage of base cations that the soil can hold (M. He et al., 2021). It depicts the ability of the soil to adsorb and retain cations and be able to exchange same (Zhang et al., 2021). Soil CEC is closely related to the colloidal substances and clay particles and has been reported to be impacted by biochar application (Jien and Wang, 2013; Thammasom et al., 2016; Tsai and Chang, 2019;Wacal et al., 2019). The mechanism involves the decomposition of biochars organic matter or C which increases the CEC of the soil (Zhang et al., 2021). Similarly, the release of organic acids from biochar, and the dissociation of these acids causes a net negative charge within the soil (Rahman et al., 2020). These charges trigger the retention of cations through electrostatic interactions, thereby increasing the overall CEC of the soil (Mbagwu and Piccolo, 1997). Furthermore, the presence of carboxyl functional group and high surface area of most biochars are also other factors that help biochar increase the overall CEC of soil (Sohi et al., 2010). It is important to note that when applied to soils, crop straw biochar generally produces higher CEC than animal manure biochar (Rahman et al., 2020).

Despite many researches that have affirmed the positive effects of biochar on soil CEC, contrary findings have also been reported. According to Romualdo et al. (2018) the effect of biochar application on soil CEC varies. This assertion was confirmed by Hailegnaw et al. (2019) who demonstrated that biochar effects on soil CEC is not uniform. According to the authors, increases and decreases of CEC in different plots was due to the initial exchangeable Ca^{2+} of the soils with soil that had higher initial Ca^{2+} than the biochar recording decreases in CEC and vice versa. This finding suggests that the soil initial properties play a key role in biochars effect soil CEC.

2.3.2.4.3. Soil organic matter

Soil organic matter (SOM) is the primary indicator of soil fertility status (Cai and Chang, 2016) and the potential of soil to support optimum plant performance. Soil organic matter or carbon is positively affected by the addition of biochar to the soil and has been widely reported (de Jesus Duarte et al., 2019; Mehmood et al., 2020; Joseph et al., 2020). The primary mechanism is through direct C addition to the soil (Bista et al., 2019). Biochar's C stability in the soil is considered a key characteristics of biochar (Steiner et al., 2016) that ensures C sequestration into the soil and accumulates mostly within the first 45 cm depth of soil (Soinne et al., 2020). Biochar's C can range from as low as 172 to as high as $905gCkg^{-1}$ (Chan and Xu, 2009) and has been estimated to last over hundreds of years in the soil, with a potential to improve soil productivity beyond its fertilizer effects (Lorenz and Lal, 2018). Although the biochar's C is relatively stable and long lasting in the soil, it is not permanently immune to mineralization (Mukome and Parikh, 2015). The direct mineralization of C inherent in biochar still occurs and is believed to be the main pathway through which biochar increases soil organic carbon (Yao et al., 2017; Karim et al., 2020). Studies suggest that soil organic carbon or matter accumulation in soil after biochar addition positively correlates with application rates (Joseph et al., 2020; Bista et al., 2019; Luo et al., 2020). On the other hand, Lima et al. (2018) found a decrease in total soil carbon content after biochar addition which suggests that the effect of biochar on soil carbon and organic matter might be short-lived.

2.3.2.4.4. Soil electrical conductivity (EC)

Electrical conductivity (EC) defines the ability of a material to conduct electricity and it is used as a proxy for estimating salinity of soil (Mukome and Parikh, 2015). Electrical conductivity of a soil is affected by different factors and constantly varies according to management practices. Apart from pH, electrical conductivity is the most frequently measured soil properties after biochar application (Singh et al., 2018). The need to measure this parameter stems from different reasons: a) role of electrical conductivity on soil aggregation (Joseph et al., 2009), (b) the potential salt build–up when biochar is applied to the soil without proper measurement, which is caused by enhanced mineralization and solubilisation of ions (Rahman et al., 2020; Gliniak et al., 2019). The large surface area of biochar also enhances cations adsorption which leads to increase in soil electrical conductivity (Gliniak et al., 2019). In a 60-day soil incubation experiment, the application of coal gas biochar was shown to improve the electrical conductivity of soil (Shar et al., 2021). The level of improvement observed however depended on the characteristics of the applied biochar (Domingues et al., 2017) which itself is determined by the pyrolysis temperature (Brewer and Brown, 2012) and biochar feedstock. Biochars pyrolyzed at high temperature possess higher electrical conductivity than those produced under lower temperatures (Kookana et al., 2011).

Despite its potential to promote nutrient availability for plants' use, reports have shown that increase in electrical conductivity due to biochar amendment could be detrimental to the activities of certain microorganisms, example phosphomonoesterase (Yang et al., 2020). High salt build-up and increased salinization following biochar addition could result in toxicity to activities of soil micro-organism. A similar view has also been expressed by Godlewska et al. (2021) who stated that electrical conductivity is one of the main factors responsible for biochar toxicity. It is therefore crucial that soil electrical conductivity is closely monitored after biochar application.

2.3.2.5. Effects of biochar on soil biological community

Microbes are important and integral part of the soil ecosystem and their activities and diversity are particularly enhanced by the presence of soil organic matter. Beneficial soil biota play significant role in nutrient cycling and enhance plant growth by stimulating the nutrient supply as well as help plants devise mechanism to cope with biotic or abiotic stress within the soil-plant ecosystem (Pathy et al., 2020). They also play important role by altering the bioavailability of plants nutrients (Chew et al., 2020). Through their activities, they degrade organic matter in the soil, releasing nutrients into the soil for plants uptake and their own utilization.

Biochar is similar in most specifications to organic matter. They are both largely composed of carbon and as such its addition to soil plays similar role in enhancing the population, diversity and activities of soil biological community as organic matter. However, unlike soil organic matter, biochar's addition to agricultural soil stimulates a rather complex reaction from the soil biota community. Their degradation is not also as easily as soil organic matter due to the recalcitrant nature of their C content (Lehmann et al., 2011). The difficulty in the degradation of biochar C also stems from the variation of their nutrients' components. Therefore, it is expected that the reaction of biota community to the application of biochar should also vary from soil organic matter.

Consequently, different studies have been conducted to investigate the influence of biochar application to soil biological community. These studies have yielded different but mainly positive results. Significant positive increase in microbial biomass was reported (Li et al., 2016; Ullah et al., 2020). This increase was attributed to changes in the availability of both micro and macro-nutrients and soil fauna habitats. In agreeing with this finding, Yoo and Kang (2012) noted that the increment in microbial population after biochar addition is as a result of increased substrate availability especially nitrogen on which the micro-organisms thrive. Similarly, the availability of other soil nutrients such as phosphorus, soil organic carbon and potassium necessary to support the growth of microorganisms are also enhanced by biochar application (Li et al., 2016). More than 121 bacterial taxonomic units were found to respond strongly to biochar based compound fertilizer, with 75 responding positively while 46 responded negatively (Chew et al., 2020). The stimulatory effect of biochar on soil pH (Li et al., 2016; Ghorbani et al., 2019; Anawar et al., 2015; Ji et al., 2019) promotes the activities of micro-organisms (Van Zwieten et al., 2015). Increase in soil pH also improves both the physical and chemical soil properties which favours biological activities in the soil (Li et al., 2017).

But on the other hand, the impact of biochar on soil biological community appears different between micro-organism and larger organisms. Decrease in the population as well as diversity of large sized soil fauna after biochar application has been reported (Briones et al., 2020;).

While Whalen et al. (2021) reported a none significant difference on earthworm population in both biochar amended and control plot. Thus, validating the assumption that biochar application affects soil biota differently. Various researchers have also reported increases in bacteria population after biochar application against the decrease observed in fungi population (Li et al., 2016; Chen et al., 2013). The observed difference in biota population was attributed to biochar-induced change from acidic or mild acidic condition of the soil to alkaline. Another factor which also favours the growth of bacterial as against fungi is the smaller size fungi, which helps it to easily colonize the tiny pore spaces of biochar (Li et al., 2016). Biochar induced toxicity especially at high rate is also believed to decrease fauna population in soil following biochar application (Liu et al., 2020; He et al., 2021). Thus, Khadem and Raiesi (2017) have posited that the optimum biochar application rate that stimulates the best performance of soil microorganism is between 40 and 45 $tonha^{-1}$. Although, this may vary between soil. For instance, biochar application to clay and sandy soils elicited varying changes in microbial community structure between the two soils, with greater influence on sandy soil which was linked to the liming effects of biochar application and low quality of sandy soil (Senbayram et al., 2019; Khadem and Raiesi, 2017). Apart from the chemical properties, physical properties of the biochar such as pore structure and surface area are also critical in determining how different biochars affect soil biota (Lehmann et al., 2011) and depend on both production condition and feedstock. Differences in feedstock materials endear different properties to biochar and as such leads to varied impact to soil micro-organisms. Application of biochar with a C:N ratio higher than 25-35, results in increase in soil microbial activities (Rahman et al., 2020). As with biochar feedstock, biochar production conditions also determine biochar influence on soil micro-organisms. Inhibitory effects of biochar especially those produced under low temperature (Cayuela et al., 2013) might be accountable for the reported reduction in microbial activities.

2.3.2.6. Biochar application and crop yield

Various researchers have reported varying results on biochar contribution to crop yields. Most of these researchers have reported yield increases following biochar application (Ye et al., 2020; Liu et al., 2013; Li et al., 2020). Yield increases have been attributed to different factors and mechanisms. Fernanda et al. (2019) attributed yield increase after biochar application to biochar-induced increase in nutrient use efficiency. While Van Zwieten et al. (2015) believes that improvement in the activities of certain microorganisms following biochar application is responsible for the positive changes following biochar application. According to authors (Nguyen et al., 2021; Fernanda et al.,2019) yield increase after biochar application is caused by biochar-induced increase in cation exchange capacity and exchangeable bases. For soil which are particular infertile, crop yield improvement after biochar application is attributed to direct nutrients supply by biochar or enhancement in nutrient availability due to improved soil physical, chemical and biological properties following biochar application (Lashari et al., 2015). Other researchers have also noted that no single factor could be credited for the improved crop yield following biochar application but a combination of the interaction of biochar properties. For instance, Kimetu et al. (2008) revealed that doubling of maize yield after biochar addition could not be explained by nutrient availability but factors other than plant nutrition. Similar view has also been expressed by (Ghorbani et al., 2019) who observed that biochar-induced improvement in soil properties results in reduction in nutrient loss, and promotes the availability of soil nutrients for plant uptake.

It is important to state that responses to biochar application to soil differ among crops. This was demonstrated by Farhangi-Abriz et al. (2021) who in their meta-analysis reported 28% and 13% increase in grain yield of maize and wheat respectively and insignificant effects on other crops by biochar. Furthermore, in highlight this heterogeneous response of crop to biochar application, Liao et al. (2020) reported a non-significant variation in the yield of maize and reduction in that of wheat under biochar amendments. In a six year trial of the effects of biochar on crop yield and greenhouse gases emissions, Liu et al. (2019) revealed that across the years, biochar had no effects on grains yield of rice except for a marginal increase in one of the years. These varying reports seem to emanate from the diverse environments under which biochar experiments are carried out and the generally differing characteristics of biochar.

Researches also seem to suggest that the effects of biochar additions are more pronounced on soils with poor nutrient statuses. The findings of Jeffery et al. (2017) who reported 25% increase in yield in tropical soils and a non- significant effect on temperate soil appears to corroborate this argument. According to these authors, the high nutrient status and moderate pH values of temperate soils leave little room for further improvement in soil chemical properties and hence are responsible for the non-significant improvement to crop after biochar application in temperate soils. But in contrast, under tropical environment, biochar improved crop yield through liming and fertilization effects (Jeffery et al., 2017). These contradictory findings have reconfirmed the non-universality of biochar benefits to soils and the need to harmonize experimental procedure and reporting format for biochar amended experiments. This is particularly, important as it will offer a concrete knowledge on the most effective and efficient ways through which biochar can be deployed for maximum benefits both on the environment and in agriculture.

2.3.2.7. Role of biochar on greenhouse gases emission

The increasing trend of atmospheric content of CO_2, CH_4 and N_2O is raising serious global concerns (Ralebitso-Senior and Orr, 2016; Hillel, 2003). The current atmospheric content of CO_2 for instance is >40 times what it was pre-industrial era (Shah et al., 2020) while methane has shot to more than 150% since 1750 (Jeffery et al., 2016). To arrest this trend, frantic efforts are being made to cut down on emission by reducing anthropogenic activities known to enhance greenhouse gas emission.

Soil is recognised as both source and sink of all three major greenhouse gases (CO_2, N_2O and CH_4) (Shah et al., 2020). Soil through its global N and C cycles, emits these gases into the atmosphere. However, the amount emitted strongly depends on the management practices or level of disturbance of the soil. Therefore, proper management is a key to the mitigation of greenhouse gases emission from the soil. Ideally, management practices which increase the storage of soil organic carbon in the soil through carbon sink, translates to climate change mitigation process. Biochar application to soil has evolved as key management practice that sequester carbon into the soil and in recent years has been used to mitigate greenhouse gas emission (Kumarathilaka et al., 2015; Kookana et al., 2011) without reducing crop productivity (Wang et al., 2012). The potential of biochar to enhance this process and abate greenhouse gases emission have been the driving force behind its increasing utilization. It is estimated that more than 15 tons of carbon can be sequestered into the soil in a single season by applying 45 ton/ha of biochar (Yang et al., 2020) while decreasing CO_2, CH_4 and N_2O emissions by more than 20%, 124% and 80% respectively.

The mitigatory impact of biochar on the three main GHGs are appearing contradictory. In most cases, the inhibition of one leads to the emission of the other. The varying conditions under which each of these gases is produced may be responsible for the contradictory trend. For instance, application of biochar in rice paddy significantly inhibited the production of N_2O, but not CO_2 (Awad et al.,2018). This is because CO_2 is mainly produced under aerobic condition while N_2O thrives under both anaerobic and aerobic condition. A significant decrease of about

67% in N_2O has also been reported (Li et al., 2020) following biochar addition to a vegetable soil. The mitigation of emission from soil by the application of biochar is not limited to N_2O or CO_2 alone but also to CH_4. It is estimated that the conversion of rice residues into biochar can mitigate about 80% of CH_4 emission from rice field (Knoblauch et al., 2011). Biochar's mitigatory effect on methane emission is most significant under paddy environment compared to other environments (Jeffery et al., 2016). By increasing soil aeration and soil structure, biochar application reduces the anaerobic status of a paddy soil and hence mitigates methane emission. Biochar-induced increase in soil pH which favours the growth of nitrous oxide reductase which is inhibited under acidic condition (Van Zwieten et al., 2015) also limits N_2O production. Also increase in Nitrous Oxide Reductase (*nosZ*) genes abundances and nitrification rate following biochar application results in decrease and increase in N_2O emissions respectively (Ji et al., 2019; Li et al., 2020). Similarly, the low degradability of biochar's carbon (Lehmann et al., 2011; Ralebitso-Senior and Orr, 2016) which reduces substrates availability for the microbial production of both CH_4 and CO_2 are other pathways through which biochar inhibits the emission of GHGs. Furthermore, Sochi (2010) has noted that the presence of mainly stable aromatic forms of organic carbon in biochar which cannot readily be returned to the atmosphere as CO_2 even under favourable environmental and biological conditions, such as those that may prevail in the soil are key mechanism of biochar mitigation of GHGs. An assertion which has been corroborated by Cayuela et al. (2013) who revealed that biochar properties are responsible for the mitigation of N_2O emission from soil after biochar application.

2.3.2.8. Biochar based chemical fertiliser, carbon sequestration and paddy rice productivity

Different authors have documented biochar's potential in mitigating agriculturally induced greenhouse gas emission and environmental contamination (Liu et al., 2019). Biochar application is seen as a win-win strategy for food security and carbon sequestration. However, the sustainability and the sole use of biochar for commercial agriculture have been questioned especially given the high cost of biochar production and the overwhelming need to increase food production. The cost of biochar has limited its application by farmers to not more than 5 $tonha^{-1}$ (Chew et al., 2020) while the growing world population is putting more pressure on researchers to find a more radical solution to the problem of food insecurity. Additionally, depending on the biochar production material, biochar on its own can have a relatively low mineral content and thus incapable of ensuring adequate plant productivity (Liu et al., 2019). Hence, sole application of biochar cannot guarantee adequate global food security. As a result, biochar-based fertilizer is being advocated. Already, biochar based commercial compound fertilizers exist in China, and with other amendments have been documented to increase crop yields and modify soil properties (Chew et al., 2020; Ullah et al., 2020; Dangi et al., 2019). Biochar based fertilizer has equally been reported to limit N_2O production (Zhou et al., 2021) while enhancing food productivity. The mechanism through which this fertilizer mitigates N_2O production is inferred to be through the reduction of water-soluble organic nitrogen and its activities on N-recycling enzymes. Similarly, a decrease in N_2O emission was also reported by (van Zwieten et al., 2010). Contrastingly, Senbayram et al. (2019) reported that the addition of biochar and mineral fertilizer failed to mitigate N_2O emission under two contrasting soils. With these contradictory findings, it is important that more studies are conducted to investigate the impact of biochar-based fertiliser on crop yield and GHGs emissions.

2.3.2.9. Effect of tillage practices on greenhouse gases emission and crop yield

Tillage practices play multiple and significant roles in the soil especially in the production and consumption of GHGs (Ahmad et al., 2009). This is because it alters the soil physical and chemical properties and consequently crop yield (Sadiq et al., 2021). Particularly, conventional tillage with heavy machineries that cuts below 25 cm (Pittelkow et al., 2015) has come under lime light due to soil structure destruction as well the direct and indirect emissions of GHGs from agricultural soil (Küstermann et al., 2013). Topa et al. (2021) revealed that the use of conventional tillage results in poor aggregate soil structure and stability which leads to reduced soil carbon and nutrients in both macro and micro-aggregates of soil. Therefore, it is important to seek a management practice that can effectively curb the agriculturally derived emissions (Chen et al., 2021) while conserving the environment. In this context, reduced and no tillage practices are being advocated. No tillage practice is being promoted globally due to its effects on the agroecosystem as well as its potential to off-set agriculture-driven GHGs emissions (Maucieri et al., 2021). The system is considered as part of conservation agriculture and hence climate-smart. Although the general benefits of conservation agriculture vary according to locations, it still has wide acceptance as it is considered climate-smart (Kimaro et al., 2016). The system promotes key indicators of sustainable agricultural systems such as soil organic carbon, water footprint, and GHG emissions reduction (Rahman et al., 2021).

No tillage system which partly constitutes conservative soil management practices is believed to possess the potential to reduce the emission of N_2O from the soil by affecting N-related biophysical cycles within the soil (Wang et al., 2021). Maucieri et al. (2021) revealed that the adoption of no tillage in paddy rice production significantly reduced CH_4 emission from 12.39 to 9.55 $mgm^{-2}h^{-1}$. In comparison to the conventional tillage, no tillage is considered a viable alternative in the mitigation of GHG emissions (Bayer et al., 2014). The intensive tillage associated with conventional tillage accelerates the degradation of soil organic matter and consequently undermines soil conservation (Bista et al., 2017). No tillage system limits oxygen supply to the soil and hence reduces both the microbial respiration and oxidation rate of the atmospheric methane, thereby mitigating the emission of CO_2 and methane and consequently leading to the sequestration of carbon and N in the soil (Ball et al., 1999).

In order to identify the best tillage practices that favour both crop production and soil conservation, different studies have been conducted in different parts of the world. For instance, in Germany, Struck et al. (2020) used a closed static chamber to assess the effect of tillage practices on GHG emissions and reported 47% reduction in GHG emissions as a result of the deployment of no tillage practice. Also in Germany, deploying a similar method, Küstermann et al. (2013) found that reduced tillage reduced N_2O emission but this emission increased as input of fertilizer increased.

2.4. Approaches to measuring greenhouse gases emission from rice production

The measurement of greenhouse gases from rice production is very important in global agricultural greenhouse gases emission estimation. Rice production emits large amount of both CH_4 and N_2O, two gases with strong radiative forcing and are long lived. Generally, there are two basic approaches used in the estimation of greenhouse gases. They include direct and indirect measurement (Kuyah et al., 2016). The indirect methods of estimating greenhouse gas emissions involves the use of proxy data or materials or sets of predefined equations from popular agencies like Inter-governmental Panel on Climate Change (IPCC) for the determination of GHGs (Zaman et al., 2021). The method is usually employed where there is a lack of facilities for the direct measurements from the field (Kuyah et al., 2016). On the other hand, in direct measurement approach, devices for capturing greenhouse gases emitted from rice field are actually deployed to the field and real-time measurements are taken. In order to achieve this, different devices have been developed by researchers around the globe. Some of these methods and devices are as follows: a) chambers, b) mass balance technique, c) Lagrangian stochastic dispersion technique, d) eddy covariance (eddy accumulation and flux-gradient methods). Although success has been made in ensuring that these different methodological options are available to researchers to choose from, the choice of which technique to be used is largely determined by the resources available to the researcher and the researcher's research objectives (Butterbach-Bahl et al., 2016). Nevertheless, the two commonest techniques currently used by researchers for the measurements of GHGs exchange between the terrestrial ecosystems and the atmosphere are a) chamber based system of measurements (manual or automated) and b) micrometeorological measurements (e.g., eddy covariance or gradient methods) or the combination of the two techniques (Denmead, 2008). Each method has its merits as well as its demerits and these factors also form an integral part in aiding a researcher decides which to adopt.

2.4.1. Chamber system of measurement

Chamber system of measurement is about the most popular system among researchers basically due to its simplicity, affordability and portability. The technique allows gas measurement within a small area with a chamber covering an area of soil <1m^2 and as such, more suitable for smallholder farmers (Rosenstock et al., 2016). Its operational principle is the restriction of air volume within a space where gas exchange occurs in order to magnify the concentration of the air within the headspace (Denmead, 2008). Depending on how they are operated, different types of chambers can be distinguished and include: open or flow through-chamber and closed chamber.

2.4.1.1. Open or flow through-chamber

In the open chamber, the head space of the chamber is kept open and a mass of air is allowed to constantly pass through and the difference in concentration between the air entering the headspace and that leaving it is measured.

Gas flux is calculated as F= $V(\frac{gl-gi}{A})$ ……………………………………………..equation 2

where F is the gas flux, V the volume flow rate, gl gas concentration of the air leaving the chamber, gi gas entering the chamber while A is the surface area covered by the chamber (Denmead, 2008).

2.4.1.2. Closed static chamber method

This system involves placing an enclosure over a space and allowing the air concentration to build up to the head space. In this approach, there is little or no exchange of air between the enclosure and outside. This system is preferred over the closed chamber because concentration changes are easier to detect and are mechanically simpler compared to open chamber (Denmead, 2008). Closed chamber can be static or dynamic. In the static chamber, an enclosure is made of a particular area and a syringe is used to collect gases that build up within the enclosure of the chamber and taken to the laboratory to be analysed, usually with gas chromatography. But on the other hand, dynamic chamber also possesses an enclosing platform and is either manual or automatic. This system can be particularly, important when measuring reactive gases and when there is concern about possible inhibition of gas production due to pressure build up under static chamber approach (Rosenstock et al., 2016). The manual or automatic describes the opening and closing of the lid of the system. The key difference between static and dynamic chambers is that in dynamic chamber, the gases are measured in-situ with a sensor fitted on the chamber for measuring and analysing the gas flux while for static, the gas must be collected with a syringe and injected into a vial or be taken with the syringe like that for analysis at the laboratory.

The major advantage of chamber system is its affordability, simplicity and portability while the major disadvantage is that chamber can be very sensitive due to the large increase in concentration (Denmead, 2008). Soil also varies spatially, meaning that measurement from two chambers within a close range can vary due to variation in soil properties (Rosenstock et al., 2016).

2.4.2. Backward lagrangian stochastic dispersion technique

This method is applicable to a well-defined source area and uses a Lagrangian model of atmospheric dispersion to calculate surface flux density (F_0) from the measurements of gas concentration and the turbulence at the atmosphere at any height downwind and for any condition (Denmead, 2008). The backward lagrangian dispersion technique model predicts the ratio of gas concentration to surface flux by tracing particle trajectories backwards from the sensor to source area in about 50,000 particle trajectories. The number of particle touchdowns inside and outside source area are noted and the vertical velocity of each particle at touch down is calculated (Denmead, 2008).

Backward Lagrangian Stochastic dispersion technique is credited for being very effective over a well-defined source area. It is highly recommended for assessing emission from animal production as well as treated fields. Its major demerit is the parameterisation of turbulent transport (Denmead, 2008).

2.4.3. Micrometeorological system of measurement

This is a very capital-intensive approach to GHGs measurements. Some of the very popular approaches in this design include eddy covariance, eddy accumulation and relaxed eddy accumulation. This method requires an extensive and homogenous source area with a significant fetch >1 ha and are very capital intensive (Rosenstock et al., 2016). However, the approach is more accurate than the other approaches. For instance, the eddy covariance is a very direct approach with little ambiguity. It gives the vertical flux at the point of measurement and is independent of atmospheric stability and simplifying assumptions that apply to other micrometeorological systems. Similarly, eddy accumulation is considered an improvement over eddy covariance and eliminates the need for a fast response gas analyser in the system and is very suitable for trace gases measurement. Furthermore, due to the theoretical and technical problems associated with eddy accumulation, relaxed eddy accumulation was developed. In this approach, although gas sampling is different, a fast solenoid valve is utilized to substituted for a fast response-sensor. The method involves sampling of air at constant rate and getting the air diverted into the up and down bins. Just like eddy covariance, this method also measures gases directly with an added advantage of off-line measurement although the method is still as expensive as the eddy covariance (Denmead, 2008).

2.4.4 Mass balance method

Another important system for measuring greenhouse gases emission is the mass balance method. This method equates the rate of gas production within a controlled volume to the difference between the rate at which gas is transported out of the volume and into the system by wind (Denmead, 2008). The method is also sub-divided into closed system, open system and circular plot system. The major advantage is that it is considered to be in between the chamber and micrometeorological approaches. It is considered an improvement of the chamber method and also bridges the gap in terms of material requirement of the micrometeorological approaches which require an extensive and uniform source areas (Denmead, 2008).

2.4.5. Flux-gradient method

Another noble approach used for the quantification of GHGs emissions from field is flux-gradient approach. The governing principle of this approach is relatively simple and the required equipment especially when using tracers are almost as affordable and portable as the use of chambers. This method employs a difference in concentration gradient in quantifying emissions. The basic underlying approach involves the calculation of fluxes as a product of an eddy diffusivity and the vertical concentration gradient of the gas or the product of a transfer coefficient and the difference in gas concentration between two heights. Another flux–gradient approach requiring fewer assumptions is to use tracers such as heat, water vapour and CO_2 whose fluxes can be measured unequivocally. The flux of the gas of interest is calculated as the product of the tracer flux and the ratio of gradients or concentration differences of tracer and gas measured simultaneously (Denmead, 2008). The use of tracers makes the estimation of gases relatively simple

Based on the resources available, accuracy of results obtained as seen in literature and simplicity of its use, we adopted and used the gas chromatograph static chamber technique for our study.

CHAPTER THREE

3.0. MATERIALS AND METHODS

3.1. Materials

3.1.1. Study area

The experiment was carried out at the AfricaRice research field M'be, Bouaké (7°52'10.692" N, 5°6'57.512" W) Côte d'Ivoire (Figure 4), with an elevation of 298 m above sea level. The area is within the M'be river catchment (Hakkeling et al., 1989) and the Sudano-Guinea zone; a transition zone between the forest zone and the savannah zone of the northern Côte d'Ivoire. The surrounding vegetation mainly consists of scattered trees and tall grasses with patches of primary and secondary forests (Hakkeling et al., 1989). The rainfall in the area is bi-modal with a long dry period in between (November to February) (Dossou-Yovo and Saito, 2021). The first rainy season occurs between April and June, and the second, from September to October (Hakkeling et al., 1989). The averages annual rainfall and temperature during the long rainy season are 618 mm and 21^{0}C, respectively (Dossou-Yovo and Saito, 2021).

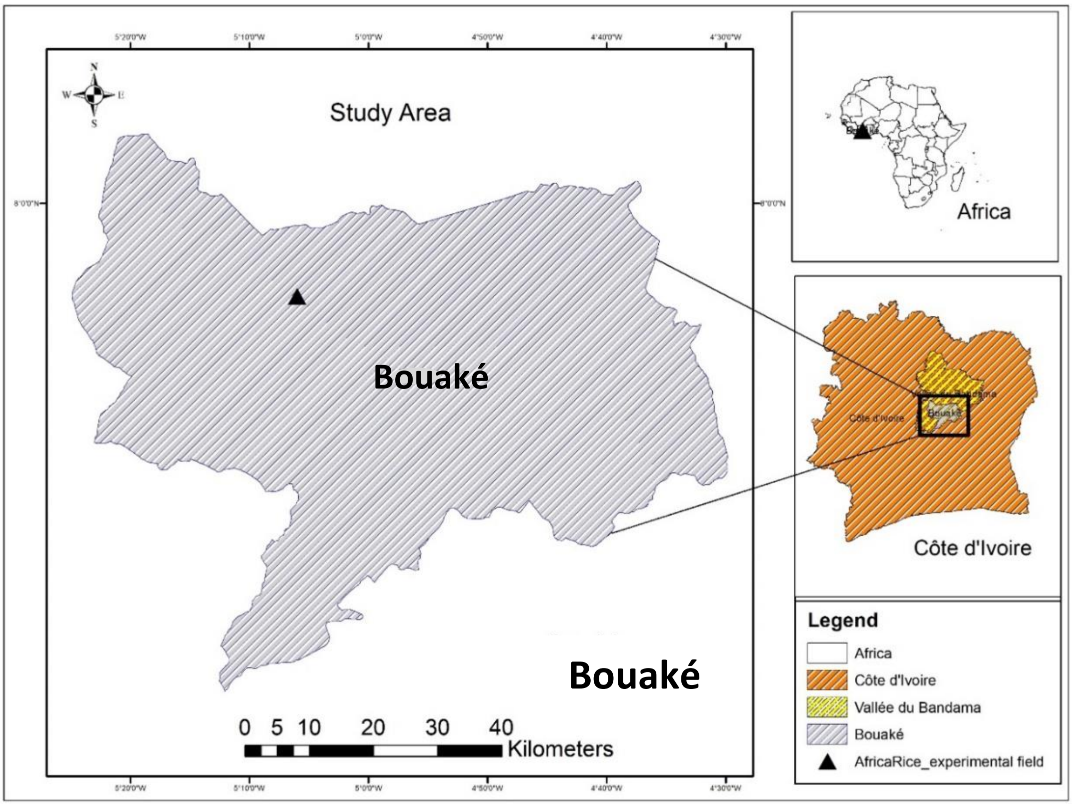


Figure 4: Map of Côte d'Ivoire showing the study area (generated during the study)

The soil of the area is derived from weathered granite and metamorphic rocks. Consequently, quartz is its dominant soil mineral (Hakkeling et al., 1989). The soil is moderately acidic with low fertility, poorly drained, deep and is classified as Gleyi-eutric Fluvisols according to FAO (Hakkeling et al., 1989).

3.1.2. Genetic material

WITA9 rice variety was used for this study. WITA 9 is a product of a cross between IR 2042-178-1 and CT 19 and was developed in 1984 by West African Rice Development Association (WARDA), a then subsidiary of International Institute of Tropical Agriculture (IITA) (Saito et al., 2019). It is a low land rice variety that was introduced in Cote d'Ivoire in 1998 (Saito et al., 2019) and performs well under wet seeding method of establishment compared to transplanting especially in the wet season. The choice of this rice variety is because of its wide cultivation (Devkota et al., 2022) and acceptance among the local rice farmers within Bouaké region of Cote d'Ivoire. WITA9 rice variety is also known for its disease resistance (Saito et al., 2019) and is an emerging rice variety being encouraged for adoption by farmers.

3.1.3. Equipment

The equipment used to during the study included: gas chromatograph, a set of air compressor and nitrogen generator, hydrogen generator (Figure 7), soil moisture probe, pH meter, AfricaRice modified Paul Olivier's gasifier, and atomic adsorption spectrometer.

3.2. Methods

3.2.1. Biochar production and sourcing of cow dung

Biochar was produced from rice husk. The rice husk was purchased from the local rice millers at the "marché de gross" in Bouaké, Côte d'Ivoire. Before rice husk pyrolysis, the moisture content of the husk was determined using a hand-held moisture meter probe. Thereafter, the husks were loaded into the AfricaRice's modified Paul Olivier's gasifier (Ndindeng et al., 2019) and ignited (Figure 5). The gasifier was operated at a temperature of 350^0C-400^0C within the AfriceRice workshop and temperature was monitored using a double thermometer. Each batch of biochar production lasted for about 30 minutes. The operational mechanism of the gasifier involves the circulation of hot air within the gasifier through the process of convection. Uniform distribution of the heated mass of air within the gasifier is aided by an electric fan attached to the vent at the base of the gasifier without necessarily introducing oxygen into the process. The gasifier has a biochar yield of about 30%.

The cow dung for the experiment was sourced from the herders within the M′be village and dried to a moisture content of 19.3% to facilitate uniform distribution within the plot, and to ease laboratory analysis.

Figure 5: Biochar production for the study of biochar and N-fertilisation effects on GHGs emissions at M’bé, research station Bouaké, Cote d’Ivoire.

3.2.2. Experimental design, treatments applications and field management

This study was conducted using a Randomized Complete Block Design (RCBD). The choice of this design is due to the nature of treatment combinations and field where the experiment was conducted. Biochar, cow dung, fertiliser and tillage constituted the factors for the experiment. A total of twelve treatments combinations (Table 2), with three replications were used. The twelve treatments combinations and their descriptions are shown in Table 2.

Table 2: treatment combinations in the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire

Nº	Treatments	Treatment components
1	C1N2	local farmers' practice of manual tillage with hoe (C1) and medium nitrogen (N) fertilizer rate, 120 kg N/ha (N2)
2	N2	No tillage + No biochar + 120 kg N/ha of nitrogen (N2)
3	B1N2	No tillage + 3 ton/ha biochar (B1) +120 kg N/ha of nitrogen (N2)
4	B2N2	No tillage + 6 ton/ha biochar (B2) + (120 kgN/ha) N2
5	BA	No tillage + B1(3 ton/ha biochar) + 5 ton/ha cow dung (CD or (A)
6	N3	No tillage + No biochar + 180 kgN/ha (N3)
7	B1N3	No tillage + B1(3 ton/ha biochar + 180 kgN/ha N (N3)
8	B2N3	No tillage + B2 (6 ton/ha biochar +180 kgN/ha N (N3)
9	B1	No tillage + B1 (3 ton/ha biochar)
10	B1N1	No tillage + B1 (3 ton/ha biochar) + 60 kgN/ha(N1)
11	B2N1	No tillage + B2 (6 ton/ha biochar) + 60 kgN/ha (N1)
12	B2	No tillage + B2 (6 ton/ha biochar)

Note: C1: hoe tillage, B: biochar, CD/A: cow dung.

For the treatments receiving nitrogen fertiliser (N), N was supplied using NPK (15:15:15) and urea (46% N) while muriate of potash (60% K_2O) and triple superphosphate (40% P_2O_5) provided phosphorus (P) and potassium (K) respectively. All treatments received equal amount of P (60 kg ha^{-1}) and K (60 kg ha^{-1}) which were applied 100% as basal fertilizer. However, due to enhanced radiation use efficiency and increased rice yield associated with split N application (Fukai and Wade, 2021; Qin et al., 2013), N was applied in three splits (50:25:25). Half (50%) of the N requirement of each treatment was applied as basal N, 25% for the first top dressing and 25% for the second top dressing. During the basal N application, NPK was used while supplemental urea was applied where NPK was unable to provide the required basal N rate for a given treatment and for top dressings.

The experiment was laid out in three blocks made up of 12 treatments per plot (Figure 6). Each plot measured 5 m x 5 m (25 m^2) and contained 25 rows of rice plants. A buffer bund of 0.40 m high and 0.60 m wide were constructed with soil around each of the twelve plots to prevent exchange of materials (treatments) between plots. A drainage canal was also created in between two parallel bunds, and was used for water management (irrigation and drainage).

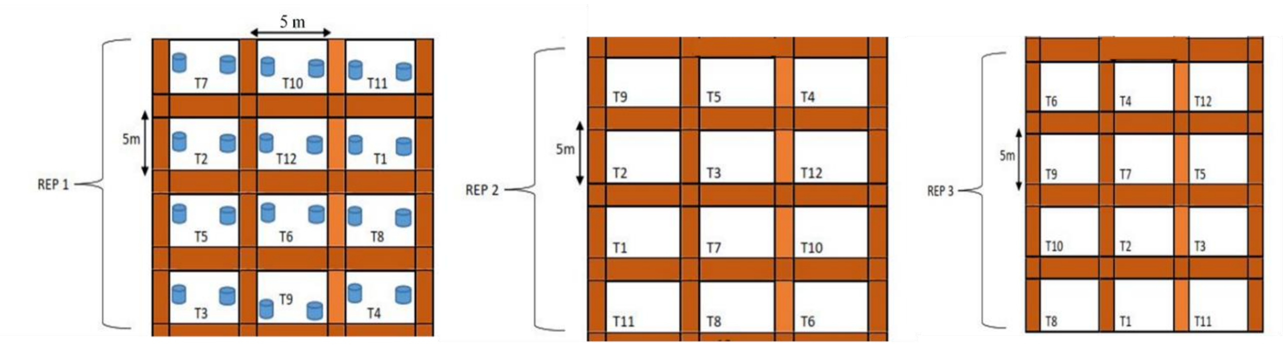


Figure 6: Field layout of experimental design for the study of GHG emissions at M'bé research station on low land rice in Bouaké Cote d'Ivoire, 2021 and 2022 cropping seasons

3.2.2.1. Water source and management in the experimental field

The water supply for the paddy field comes from a central watercourse that extends from the dam located within the M′be station. The dam is further extended to the field through canals. In combination with earthen bunds which run parallel to the experimental field, these canals convey water from the dam through the furrows into the different plots (irrigation). However, during the period of inundation, the earthen bunds are opened while the upstream part of the canal from the dam is closed, and water is drained through the furrows down to the downstream part of the canals and out of the field.

3.2.2.2 Crop and field management

The field was under a one-year fallow prior to the start of the experiment. At the onset of the experiment, the field was drained and allowed to dry. Drainage was accompanied by manual clearance using cutlass, followed by a period of non-disturbance which lasted for 14 days before being treated with glyphosate herbicide (1.0 kg/ha). The essence of allowing the field to stand for more than a week before chemical treatment was to allow the grasses to regenerate and to increase the effectiveness of the herbicide. The glyphosate treatment was done in two phases. The first application was done on 26th July while the second application was on 18th August, 2021. After the first application, the grasses were allowed to regenerate again before the second treatment application. Thereafter, the field was allowed to stand for another one week to allow the grasses to completely die before being manually cleared. The final clearance was accompanied by careful removal of both stumps and grasses from the surface of the field, followed by another short flooding period which lasted for 4 days. When all the grasses and the stumps had been completely removed, the plot receiving tillage treatment was ploughed with a hand hoe to a depth of between 5-10 cm from the soil surface. After the tillage, and before biochar application, the soil surfaces of all the plots including the zero tilled plots were gently tapped using a local rammer fabricated with low weight plank and board. The choice of low weight material was to ensure a near-zero disturbance to the soil surface during tapping. The rammer weighed about 2 kg on the average and was used to gently tap on the wet field to level off undulating surfaces and to fill up holes created by human feet so as to prevent non-uniform ponding of water or accumulation of treatment within the field.

On the 26th August, 2021 and 18th September, 2022 representing the start of first and second season trials respectively, the sieved biochar and/or cow dung were uniformly spread over the surface of all the plots receiving biochar and/or cow dung treatments. Since the experiment considered no tillage, immediately after biochar and/or cow dung application, the soil surface was gently tapped using the light weighted ramming material. This was to ensure a good contact between the soil surface and biochar which would prevent rainfall from splashing and transporting the biochar to one section of the field. A day after biochar and/or cow dung application, a pre-germinated high yielding rice variety, WITA9, was seeded directly to the field using a dibbling stick at a planting distance of 20 cm x 20 cm with three seeds per hill. Ten days after seeding, rice seedlings were thinned and supplied to two plants per hill to achieve the desired plant density of 500,000 plants/ha. Basal fertilizer applications were carried out 16 days after seeding (DAS), followed by first and final top dressings at 33 and 63 DAS, respectively for the two seasons.

Weed controls were carried out using integrated weed management approach. At the early stage of rice growth (< 30 DAS), hand weeding was employed while at the later stage when rice roots were well established (> 30 DAS), a mixture of two selective herbicides; garil power (fluroxylpyr-mehyl 230.73g/l + cyhalofop-butyl 184.3g/l) and herbextra (2, 4-dichlorophenoxyacetic acid-50.53 % w/w) herbicides (1 l/ha) were used for weed management. Similarly, handpicking and “vrai lambda 50 EC” (cyhalothrine (50 g/l)) (50ml mixed with 12 litre of water) were used for insect control.

3.2.3. Data collected

Data collected and used for this study were: weather data (rainfall and temperature), soil physicochemical data, soil moisture data, rice data (rice tillers, root biomass, straw biomass and rice yield), GHGs data, data of biochar and cow dung properties. These data were collected and used at various stages of the experiment.

3.2.3.1. Soil sampling and soil, biochar and cow dung analyses.

Prior to the start of the experiment, top soil (0-20 cm) samples were collected using a 5-cm diameter soil sampling auger. A random sampling technique (zigzag format) (Braidek et al., 2007) was employed and a total of 20 samples were collected. These 20 soil samples were used to form a composite sample and further divided into three sub-samples. The sub-samples were bagged and transported to the lab for soil analyses. Before analysis and/or field application, the samples including soil, cow dung and biochar were air-dried and made to pass through a 2-mm sieve. Thereafter, the samples were determined for;

- Soil organic carbon was analysed using the wet oxidation method as described in Walkley and Black method (Walkley and Black, 1934). The procedure involves the oxidation of soil organic matter in a sample of soil with a given volume and concentration of dichromate. Thereafter the extractant is titrated using concentrated sulphuric acid.
- pH was determined by dissolving 1 gram of soil in 2.5 cm^3 of distilled water and stirred continuously for about 30 minutes. Thereafter, a pH meter electrode was inserted into the sample and the hydrogen ion concentration was read off from the meter.
- Cation Exchange Capacity (CEC) was determined using ammonium acetate method according to Chapman method (Chapman, 1965). The principle involves the leaching of 10 gram of soil and titrating the leachate with 0.05 N concentration of sulphuric acid until there is a colour change.
- Bray's method which is most recommended for acidic and ferrallitic soils was used for the determination of phosphorus. The procedure involves the use of ammonium fluoride (NH_4F) and hydrochloric acid (HCl) to extract phosphate ion and exchangeable phosphate from 5 gram of soil as described by Bray and Kurtz (1945).
- mineral elements (potassium, Manganese, Zinc, Iron, and Cupper), using atomic absorption spectrometer. The process involves the extraction of these mineral

elements (potassium, Manganese, Zinc, Iron, and Cupper) with some chemical extractants and a sample injected into the atomic absorption spectrometer where each element is then read off based on their wavelength.

- Bulk density was determined as a ratio of oven dry mass of soil to the volume of undisturbed fresh sample (volume of the core sampler) as described by Blake and Hartge's method (Blake and Hartge, 1986)

Similarly, at the end of the experiment, soil samples were also collected as indicated above but, in this case, from each of the experimental plots. In each of the plots, a total of 8 composite samples were collected using "Z" pattern. The samples were thoroughly mixed and thereafter were bagged into 3 sub-samples and transported to the laboratory for physical and chemical analyses as stated above.

3.2.3.2. Greenhouse gas and soil moisture measurements and analyses

3.2.3.2.1. Gas sampling

Greenhouse gas (GHG) measurements were only performed during the first season trial. Measurements started before field preparation (Figure 7 A) and continued until rice harvest. Late arrival of GHG measurement equipment from maintenance prevented GHG measurements during the second season experiment. During the first season, GHG measurements were conducted using the closed static chamber method. Prior to seeding after treatment application (Figure 7 B), one base frame collar made of stainless steel was permanently installed 10 cm into the soil in each of the plots (at the distance of about 1.5 m into the plot from each side) (Figure 7 C). The collars measured 54.0 cm, 33.5 cm, and 15.0 cm in length, breadth and height respectively. Each of the collars was also equipped with a trough of 3.5 cm depth and 4 cm width where the chamber sits during gas sampling (Figure 7 D). Similarly, wooden walk-boards (Figure 7 E) measuring 2 m each were also permanently installed in the plots (indicated with an arrow). To minimize the number of walk-board needed, the boards were installed close to the collars in each plot (Figure 7 E). The installation was such that one board stretched from the end of a collar in one plot, and over the demarcation bunds to another collar in the adjacent plot. These boards provided a walk path during gas sampling to prevent gas ebullitions and soil disturbances.

Figure 7: Field gas sampling before treatment application (A), field after treatment application (B), installation of collars (C), gas sampling before rice germination (D), installation of walking board and gas sampling after rice germination (E) and gas sampling at heading stage (F) during the first rice growing season at AfricaRice research station, Mbe, Cote D'ivoire

Gas chambers made of transparent plexiglass material with aluminium frame with dimensions of 59 cm x 40 cm x 60 or 108 cm were used for gas measurements at the early rice growth stage (Figure 7 D, E). From the heading stage, higher chambers with the dimensions 59 cm x 40 cm x108 cm (Figure 7 F) were used. The chambers were equipped with fan, for air circulation within the chamber, thermometer for taking the temperature within the chamber during gas sampling and a vent tube made of cupper which was slightly bent at the top and measured 10 cm for equilibrating the pressure within and outside the chamber (Feng and Zhu, 2017). At each gas sampling period, the chambers were mounted on the groove or trough of the permanently installed collars, and the trough was filled with water to create a gas seal between the collar and the chamber to prevent gas leakages during gas sampling. The frequency of gas sampling was once a week between 8: 30 A.M and 12 noon. However, after each fertilization event, gas sampling was intensified to once every two days for six consecutive days. At each sampling event, four gas samples were collected immediately after chamber closure at 0, 10, 20 and 30 minutes using a 30 ml plastic syringe equipped with a needle and a 3-way stopcock. The syringe was pumped for at least 5 times to ensure that the air within the chamber is well mixed before sampling. The collected gas was immediately injected into a pre-evacuated 20 ml vial bottles.

After sampling all the plots, all vials filled with gas were immediately transported to the laboratory for GHG analysis. The basic analysis principle and process involved loading the gas-filled vials into an auto-sampler (Figure 8 A) with 42 vials capacity. After loading, the auto-sampler takes 5 ml from each of the vials and injects into the gas chromatograph (GC) machine (Figure 8 B) where the gases are passed through the columns located within the GC oven and the component gases are determined as the gases pass through the columns using the various detectors. The concentrations of CH_4, and N_2O were analysed simultaneously using a gas chromatograph (SRI 8610C, gas chromatograph, Germany) equipped with Flame Ionization Detector (FID) and Electron Captor Detector (ECD). The oven, FID and ECD were operated at 82^0C, 306^0C and 354^0C temperatures respectively. The FID and ECD detected CH_4 and N_2O respectively. Pure nitrogen (>99.999%) generated from the nitrogen generator (Figure 8 C) and hydrogen (>99.999%) from hydrogen generator (Figure 8 D) were used as a carrier gas, and fuel gas respectively while zero air from air compressor (Figure 8 E) was used as a make-up gas.

Figure 8: Gas chromatograph system: (A= auto-sampler for taking of gases from vials, B= gas chromatograph equipped with gas detectors, C= nitrogen generator for the detection of N_2O, D= hydrogen generator for the detection of CH_4 and CO_2, E= air compressor for generation of pure air, D=visualizing the chromatogram of gases)

Greenhouse gas flux was calculated using a modified flux equation according to (Dossou-Yovo et al., 2016; Qin et al., 2016).

$$\text{flux} = \rho^{\times} \frac{dc}{dt} \times \frac{273}{273+T}{}^{\times} H^{\times} 1000^{\times} 60 \text{……………………………………..………(Equation 1)}$$

Where ρ is the reference gas density (CH_4, and N_2O), H is the chamber height, dc/dt is the slope of gas concentration from the GC, T is the temperature within chamber, 1000 is the conversion factor from gram to milligram, 60 is the conversion from minutes to hour.

The cumulative emission was calculated according to (Dossou-Yovo et al., 2016).

$$C_{\_flux} = \sum_{i=1}^{n} \frac{F_{i+1}+F_i}{2} * (t_{i+1} - t_i) * 24 \text{………….……………..………………… (Equation 2)}$$

Where C_flux is the cumulative emission; Fi, the flux of CH_4 and N_2O ($mgm^{-2}d^{-1}$) at the ith measurement; Fi+1, the next measurement at ti+1; ti+1-ti is the interval between two successive measurements; n is the total number of measurements.

Global warming potential (GWP) and greenhouse gas intensity (GHGI) were estimated using equations (3) and (4) respectively (Wu et al., 2019b);

$$34 * CH_4(TCH_4kgha^{-1}) + 298 * N_2O(TN_2Okgha^{-1}) \text{…………………….………..…(Equation 3)}$$

$$GHGI = \frac{GWP}{grain} \text{…………………………………………………………………………(Equation 4)}$$

where the numbers 34 and 298 are respectively the radiative forcing potentials of CH_4 and N_2O gases over a 100-year timescale under a climate feedback scenario (IPCC, 2013).

At the end of the experiment, treatments effect on carbon sequestration was calculated using equation 5 (Han et al., 2022; Koyama et al., 2015; Xu et al., 2020)

Carbon sequestration $\left(\frac{\mathrm{kgC}}{\mathrm{ha}}\right) = \mathrm{C_1} - \mathrm{C_0} * \mathrm{BD} * \mathrm{H} * 100$……………………..………..(Equation 5)

Where C_1 and C_0 are respectively the soil organic carbon content (g/kg) at the beginning and end of the experiment, BD is the soil bulk density (g/cm3) at the end of the experiment, H is the sampled soil depth (cm).

3.2.3.3. Temperature, rainfall, soil moisture content

Air temperature inside the chamber and moisture within each experimental unit were respectively taken using internally attached thermometer and a hand-held moisture probe (ML2x-KIT, Delta-T Devices Ltd., Cambridge) during gas sampling.

The air temperature and rainfall data over the area and across the rice growing season were collected from the near-by weather station (AfricarRice station, M'be).

At the end of each growing season, soil samples were taken from each of the plots for the determination of soil physico-chemical properties. The soil samples were analysed by the AfriceRice soil laboratory protocol.

3.2.3.4. Rice morphological parameters and grain yield

Root biomass, number of tillers, straw biomass and paddy yields were collected during the two growing seasons. For root and straw biomass, a destructive sampling technique was used and a total of three sampling events at 30 (tillering stage), 60 (heading stage) and 90 (ripening stage) days after sowing (DAS) were conducted. Sampling was done from the left-hand side of each plot while facing southwards. During each sampling event, first two rows from the left-hand-side and first two rows into each plot were left out to avoid biased results due to border effect. Thereafter, starting from the third rows from the left and second rows into the plot, the first five tillers (1 m) were marked moving forward into the plot, and another first five tillers rightward from the same starting point (third line from the left and second into the plot) were also marked. This sampling design resulted in marking of a total of 25 tillers in an area of 1 m^2 (1 m x1 m) per plot in each sampling event. The marked tillers were uprooted and washed in flowing water in the canal before being weighed. After weighing, the samples were sun-dried and re-weighed to get their dry weights. This was followed by the separation of the samples into aboveground and belowground biomass before being weighed separately to determine dry straw biomass and dry root biomass weights.

Paddy yield was determined at maturity using two replicates. In each replicate an area of 2 m x 2 m (4 m^2) was harvested. Two border rows were left and sampling was carried out from the succeeding lines per replication. The technique involved blindly throwing a quadrant of 4m^2 into each plot and harvesting all the tillers within the quadrant. The procedure was carried out twice to collect the representative sample for each plot. Harvested rice from each experimental plot was threshed to obtain only the grain yield while the biomass was weighed and used for the determination of harvest index (Equation 7). The grains were further sun dried for 48 hours and grain yields determined at 14% moisture using the approach described by the International Rice Research (IRRI) (Equation 6).

$$\text{Final weight (kg)} = \text{initial weight(kg)} \times \frac{100-\text{initial moisture content}}{100-\text{final moisture content}} \quad \text{(Equation 6)}$$

Using the paddy yield and total biomass yield from the harvested area, harvest index was determined according to equation 7.

$$Harvest\ index\ (\%) = \frac{\text{grain yield (ton ha}^{-1})}{\text{Stover yield (ton ha}^{-1})} * 100 \quad \text{(Equation 7)}$$

3.2.3. Statistical analyses

All data analyses were performed using R statistical software (R Core Team, 2022). The total or cumulative N_2O and CH_4 emissions, global warming potential (GWP), greenhouse gas intensity (GHGI), and carbon sequestration potential data were subjected to a one-way analysis of variance (ANOVA) (equation 8). While, two-way ANOVA (equation 9) was used to test the effects of treatments and years of experiment on the growth of rice morphological traits, grain yield and harvest index. For both one and two-way (two factors) ANOVAs, where test results were significant, means were separated using Tukey Honest Significant Difference (HSD) test ($P<0.05$). Results of analysis were presented either in tables, bar plots or graphs. Additionally, simple linear regression model was used to assess the relationship between rice morphological traits and GHGs, rice morphological traits and rice yield as well as rice yield and GHGs (Equation 10). While Pearson correlation was used to check the coefficient of the relationship and significant level tested ($p<0.05$) using TukeyHSD test.

$Y_{ij} = \mu + \tau_i + \beta_j + \epsilon_{ij}$…………………………………..……….………….(Equation 8)

Where μ is the baseline mean, τi is the i th treatment effect, βj is the j th block effect, and ϵ_{ij} is the ith treatment random error and j is the jth block random error.

$\gamma_{ij} = \alpha + \beta_i + \Psi_j + \beta * \Psi + \epsilon_{ij}$…………………………………………….…..(Equation 9)

Where γ is the response variable, β is the treatment effect, Ψ is the year effect and i and j are respectively levels of treatment and year while ϵ error term for both treatment and year effects.

$Y_j = \alpha + \beta_j + \epsilon_j$ ………………...……………………………………………(Equation 10)

Where Y is the response variable, α is the intercept and β represents the treatment while j is the levels of treatments and ϵ_j is the treatment error.

CHAPTER FOUR

4.0. RESULTS AND DISCUSSIONS

4.1. Initial soil, biochar and cow dung properties

The general properties of the soil, biochar and cow dung are presented in Table 3. From Table 2, the soil is characterised by low soil organic carbon (OC), low cation exchange capacity with mild bulk density and high cupper content. The soil can be classified as infertile and mildly acidic. Contrarily, the biochar and cow were basic and possessed both high organic carbon, phosphorus, zinc and potassium. Both the biochar and the cow dung can be categorized as basic (Table 2).

Table 3: initial soil, biochar and cow dung properties for the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice conducted in 2021 at the AfricaRice research field M'be, Bouaké in Côte d'Ivoire

Properties	**soil**	**biochar**	**Cow dung**
pH-H_2O (1/2.5)	5.98	9.64	9.21
P. bray1 (mg/kg)	3.58	35.08	26.28
% OC	2.80	7.80	36.40
CEC ($cmol^+/kg$)	0.02	0.03	0.03
K-Total (gkg^{-1})	0.23	7.07	32.41
Bulk density (gcm^{-3})	1.52	-	-
Mn-Total (gkg^{-1})	0.18	0.50	1.08
Mg-Total (g/kg)	1.05	3.16	11.36
Zn-Total ($mgkg^{-1}$)	14.85	52.51	37.49
Fe-Total (gkg^{-1})	11.73	0.99	11.80
Cu-Total ($mgkg^{-1}$)	36.54	137.96	17.23

pH: potential of hydrogen, P: phosphorus, OC: organic carbon, K: potassium, Mn: manganese, Mg: magnesium, Zn: zinc, Fe: iron and Cu: copper

4.2. Rainfall (mm) and temperature (^0c)

The daily rainfall and temperature data obtained during the 2021 and 2022 rice growing seasons were used to better understand the influence of environmental factors on the regulation of rice growth and emission of GHGs. The plot of the daily rainfall and temperatures is presented in Figure 9.

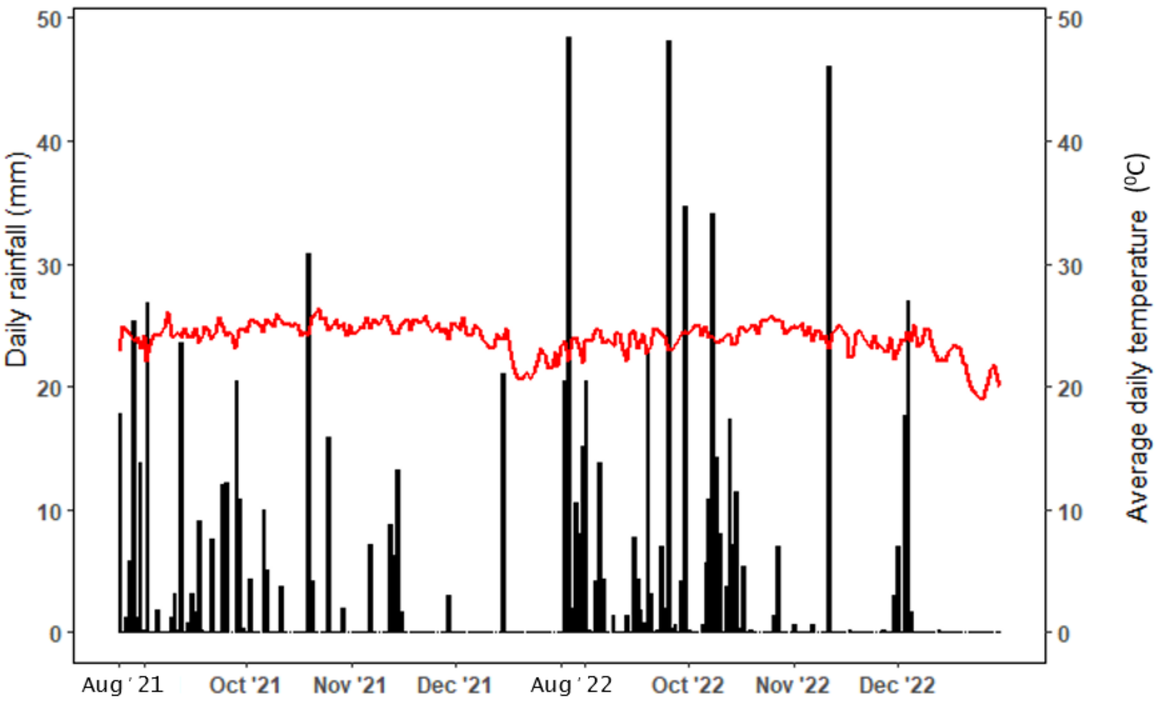


Figure 9: Daily rainfall (bars) and averages daily temperatures (red horizontal lines) at the study site (August to Dec 2021 and 2022) collected during the 2021 and 2022 rice growing seasons.

The figure (Figure 9) showed that most of the rains received in the area occurred in the months of August and September which is the main rainy season at the location. Average daily temperature fluctuation was relatively low with highest temperatures observed in early September and mid-October. Lowest temperatures were observed in mid-August and late December. Average daily temperatures were similar for the two seasons and the mean temperature (26.2 ^{0}C) for the location (Konan et al., 2022). However, higher rainfalls were observed in 2022 compared to 2021 growing season which were unevenly distributed during each of the growing months. This finding is in conformity with the result of Konan et al., (2022) who found irregular rainfall distribution for the location. Additionally, during the experiments (first season and second season), higher rainfalls were observed between August and September compared to other months. This agrees with the finding of Dossou-Yovo and Saito (2021) who observed that higher rainfalls are usually experienced in Bouake between August and October.

4.3. Effect of biochar and N-fertiliser application on GHGs emissions and rice yield

4.3.1. Soil moisture variation and temporal pattern of CH_4 and N_2O flux

Soil moisture distribution in the field during the rice growing season of 2021 is shown (Figure 8). Daily soil moisture content fluctuated significantly across the measurement days ($p<0.05$) (Table 3) and followed a similar pattern as rainfall (Figure 9). Soil moisture was at maximum during the early rice growing period (Figure 10) which coincided with the peak of the rainy season (August to September). Thereafter, the soil moisture declined gradually for all treatments as dry season approached and continued until harvest (24th December,2022). A highly significant effects of treatments and interaction between sampling days and treatments on soil moisture content were also found during the rice growing season (Table 4).

Regarding the treatment effects on soil moisture content, B2 with or without nitrogen showed higher soil moisture retention compared to other treatments at the seedling stage. Besides B2, C1N2 and N2 also promoted soil moisture retention during the early rice growth stage (Figure 8). However, as rice growth advanced, soil moisture retention pattern among treatments varied, although marginally. The treatment, N3 showed lowest soil moisture retention among the treatments at the early vegetative stage. While the positive effect of high biochar (B2) application on soil moisture with or without N persisted over other treatments until 46 DAS. Thereafter, B2N2 retained the highest amount of moisture relative to other treatments. Contrarily, at the mid-vegetative stage (51 DAS), a sharp decrease in soil moisture content was observed under (N2). While, at late vegetative stage (68 DAS) lowest soil moisture content was recorded under BA, B2N1, N2 and N3. Similar to the vegetative stage, high biochar rate (B2) with or without N, maintained higher soil moisture content under the reproductive stage (Figure 8). Beside B2, low biochar in combination with either medium N (i.e. B1N2) or high N (B1N3) or without N (B1) strongly enhanced soil moisture retention at the early rice reproductive stage. The relative higher moisture retention under high N application could be attributed to the N-induced higher rice canopy which may have decreased soil surface exposure and evaporation. Presence of shades protects soil from direct heat and hence reduces water evaporation from the soil (Harris et al., 1916). Although B1N2, C1N2 and B1N3 showed few positive changes on soil moisture retention at some stages of rice growth, the overall effect of high N application on soil moisture compared to treatments with low or no N was not evident.

Regardless of the growth stage, biochar application increased the average soil moisture content more than N application (Figure 10). Particularly, biochar application rate of 6 ton/ha (B2) appeared to conserve soil moisture especially during the late rice growing state than other treatments. Through its organic matter content, biochar when applied to soil induces the binding of soil particles (Jien and Wang, 2013; Yang and Lu, 2021) which improves soil structure and water retention capacity (Yang and Lu, 2021). About 60% increase in water retention capacity has been reported following biochar application (Jien, 2018). Relative to high N rate (N3), biochar increased soil moisture content by between 3.71% to 11.94%.

In our experiment, the role of water regimes on the temporary emission of CH_4 was masked due to the commencement of the experiment at the receding stage of rainy season (26th August, 2021). The high moisture period of the field coincided with the period of early rice growth stage which made it difficult to capture the real effect of soil moisture on CH_4 emission. CH_4 is primarily produced under anaerobic condition (high soil moisture) during the microbial fermentation of carbon (Hasan, 2014; Kogel-Knabner et al., 2010) and transported from the rhizosphere into the atmosphere through the aerenchyma tissues (Conrad, 1993). Since aerenchyma tissues develop as rice plant ages, our result suggests that the poor development of this tissue at the early plant growth stage may have inhibited the diffusion of the produced gas from the root zone into the atmosphere. Previous researchers have reported a positive correlation between CH_4 emission and soil moisture content (Yin et al., 2021; Hou et al., 2012; Lan et al., 2019).

On the other hand, the impact of soil moisture content on N_2O emission appears more evident especially under B2. Although emissions were generally higher at the late rice growing stage but the high biochar application treatment suggests improvement in soil aeration under this treatment which may have promoted the process of nitrification. Lorenz and Lal (2018) estimated in similar study that the application of biochar to soil could result in 14–64% increase in soil porosity. High porosity under suitable substrate can potentially stimulate soil nitrification process.

Table 4: analysis of variance (ANOVA) for soil moisture content, temporal pattern of CH_4 and N_2O fluxes for the different sampling dates and treatments during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire. TukeyHSD test ($p<0.05$)

		Soil moisture (%)				CH_4 (mg m^{-2} hr^{-1})				N_2O (µg m^{-2} hr^{-1})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	60	30	0.46	0.63	3429	1714.3	168.54	<2e-16	56.6	28.32	26.85	5.86e-12
Dates (D)	28	240435	8587	130.39	< 2e-16	16862	602.2	59.21	<2e-16	432.5	15.45	14.65	< 2e-16
Treatment (T)	11	4516	411	6.23	7.60e-10	5134	466.8	45.89	<2e-16	87.5	7.95	7.54	2.45e-12
D x T	308	61469	200	3.03	< 2e-16	57104	185.4	18.23	<2e-16	3129	10.16	9.63	< 2e-16
Error	694	45706	66			7059	10.2			731.8	1.05		
Total	1043	352186	9294			89588	2978.9			4437.4	62.93		
SD			8.12				3.2				1.0		
CV%			13.2				13.6				10.1		

SD: standard deviation, CV: coefficient of variation

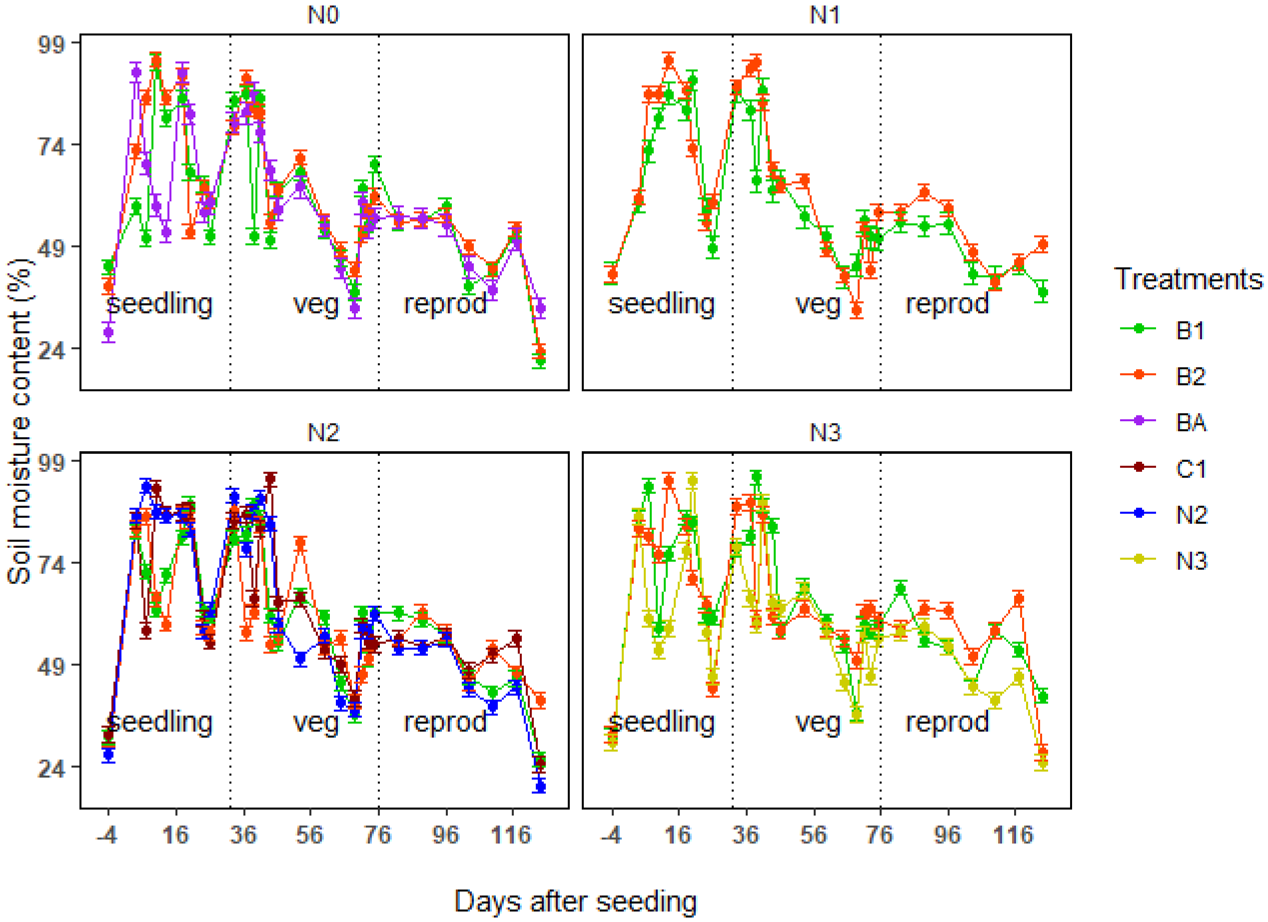


Figure 10: Temporal pattern of soil moisture distribution under different treatment applications. B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha).

4.3.2. Effects of treatments on rice morphological traits development

In order to determine whether to present the rice morphological traits data yearly or pool the two years data and conduct a two-way analysis of variance (ANOVA), the data (rice morphological trait) were subjected to homogeneity test (Levene test) (Fávero et al., 2023). According to the decision rule of homogeneity test, a significant p value ($p<0.05$) implied non-homogeneity of variance, in which case, data would be analysed using a one-way ANOVA and results presented yearly while non-significant p value implied homogeneity of variance and as such, the data would be pooled and analysed using a two-way ANOVA. The result of homogeneity test revealed a non-significant variation of variance (Table 5) and hence, the two years data were pooled and analysed using a two-way ANOVA.

Table 5: result of Levene test ($p<0.05$) for three rice growth stages (tillering, heading, ripening) during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

Parameter		Tillering		Heading		Ripening	
	Df	F	p	F	p	F	p
Tiller number	23	0.46	0.98	0.58	0.92	0.73	0.79
Straw biomass	23	1.19	0.3	0.51	0.96	0.50	0.96
Root biomass	23	1.09	0.39	0.46	0.98	0.47	0.97

DF: degree of freedom

4.3.2.1. Number of tillers

Since Levene's test showed homogeneity of variance for the rice morphological traits for each of the growth stages and for the two rice growing seasons and treatments (Table 5), the means of the rice traits at each growth stage and for the two years were pooled and analysed using a two-way ANOVA. Results of the ANOVA indicated that at tillering stage (GS1), treatment application and year as well as the interaction of year and treatment had no significant influence on rice tiller numbers (Table 6). However, as the rice growth advanced to heading stage (GS2), treatment effect on rice tiller numbers became significant but not year effect or interaction between year and treatment (Table 6). Also, at the most advanced stage of rice growth (ripening stage i.e. GS3), highly significant effect of both treatment application and year on rice tiller numbers was observed, although their interaction remained non-significant (Table 6).

Table 6: ANOVA of rice tiller numbers response to year and treatment application at the three rice growth stages (tillering, heading and ripening) during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire. TukeyHSD test ($p<0.05$)

		Tillering (tiller m^{-2})				Heading (tiller m^{-2})				Ripening (tiller m^{-2})			
Sources of variations	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	27212	13606	1.87	0.17	96084	48042	5.67	0.0063	6175	3088	0.97	0.39
Year (Y)	1	18980	18980	2.61	0.11	21935	21935	2.59	0.11	64500	64500	20.3	4.52e-05
Treatment (T)	11	146198	13291	1.83	0.076	493600	44873	5.29	2.43e-05	186166	16924	5.33	2.27e-05
Y x T	11	76901	6991	0.96	0.49	97371	8852	1.04	0.43	60448	5495	1.73	0.1
Error	46	334384	7269			389935	8477			146139	3177		
Total	71	603675	60137			1098925	132179			463428	93184		
SD			85.3				92.1				56.4		
CV			35.1				22.7				16.5		

SD: standard deviation, CV: coefficient of variation

In each of the years (2021 and 2022), rice tiller numbers varied non-significantly among the treatments (Table 7). Over 50% of the treatment showed higher mean number of tillers in year 2022 than 2021. The pooled data for the two years also indicated no significant variation across the experimental years and treatments for mean rice tiller numbers at rice tillering stage. Nevertheless, the mean tiller numbers were higher in second the year relative to first year (Table 7). Considerable arithmetic differences on mean number of tillers were observed under high fertiliser and biochar combinations (B2N3 and B1N3) as well as sole high N application (N3). Highest mean number of tillers was observed under high fertiliser and high biochar combination (B1N2) 310.834 while low biochar with no fertiliser treatment resulted in lowest number of tillers (B1) (194.83) (Table 7). With or without biochar, mean tiller numbers increased arithmetically with increasing nitrogen rate. Except for B1N2, control (C1N2) produced higher mean number of tillers than other treatments with the same N rate at tillering stage.

At heading stage, treatment application significantly affected mean rice tiller numbers in 2021 (Table 7) but not in 2022. Specifically, B2N1 resulted in highest mean tiller numbers of 545.33 tillers m^{-2} in 2021 while B1 produced the lowest (273.7) numbers of tiller m^{-2}. Despite the non-statistical significance among treatments in 2022, the minimal effect of low biochar (B1) application on rice tiller number persisted. Results from the aggregation of the two years data (2021 and 2022) showed a significant effect of treatment on mean rice tiller numbers (Table 7). However, the year effect remained non-significant. The aggregated data also showed that the lowest mean tiller numbers per m^2 (277.7) was recorded under sole low biochar application (B1) which was not significantly different from B1N2, 1N2, B2N2, B2, BA, and C1N2 (Table 6). The absence of nitrogen in B1, B2, and BA inhibited tillering at tillering stage which extended up to heading stage. Despite having the same N rates, control (C1N2), B1N2 and B2N2 all produced lower number of tillers compared N2. N2 also produced higher mean number of tillers than B1N3. This could be due to the slow release of N to plant by biochar. More than 39.4% N retention in the soil following co-application of biochar and N has been reported (Shin et al., 2021). N retention implies that biochar can act as a slow-release fertiliser to improve nitrogen use efficiency in rice cultivation (Sun et al., 2019). This hypothesis was further confirmed by higher mean tiller number (albeit non significantly different) observed at ripening stage under co-application of biochar (B1N2 and B2N2) compared to N2 (Table 7).

During the rice ripening stage, significant treatment effects were found for years 2021 and 2022 (Table 7). N3 consecutively produced the highest number of tillers for the two years while B2 application resulted in lowest number of tillers. When the two years data were pooled, significant differences were also found among treatments as well as years with year two recording higher mean value than year one. Treatments with no N combinations (B1, B2 and BA) produced the least number of tillers. As was the case in heading stage, progressively increasing N rates in the absence of biochar resulted in progressive increase in mean rice tiller numbers per m^2 at ripening stage (Table 7). Similar pattern was also obtained under low biochar rate (B1), progressively increasing N rate resulted in progressive increase in mean rice tiller numbers per m^2. In contrast, progressive increase in N rate under high biochar (B2) produced a non-linear increase in mean rice tiller numbers (Table 7). This could be an indication that the application of high biochar could cause nutrient immobilization within the soil (Gao et al., 2019) and inhibits the activities of soil micro-organisms (Cayuela et al., 2014) responsible for nutrient transformation for plant utilization.

Current results indicated that nitrogen (N) played a key role in rice tiller growth. Increase in rice mean tiller numbers following nitrogen fertiliser application has also been reported by (Wang et al., 2016). Nitrogen availability facilitates both physiological and biochemical functions of crops and can directly affect rice performance (Ullah et al., 2021). Therefore, increasing nitrogen fertiliser rates enhance the number of rice tillers by increasing N metabolizing enzymes such as glutamine synthetase and glutamine oxoglutarate aminotransferase (Ali et al., 2022). Our finding also agrees with those reported by Ghoneim and Osman, (2018) but differed from the finding of Haque et al. (2022) who reported increase in the number of tillers under higher biochar rate compared to lower rate.

Table 7: ANOVA of treatments and year effects on number of rice tillers per m^2 for three rice morphological stages during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

Treatments	Tillering (tiller m^{-2})			Heading (tiller m^{-2})			Ripening (tiller m^{-2})		
Year 1			231.1a			459.9a			312.28b
Year 2			263.6a			425.0a			372.14a
Tukey HSD (0.05) main year effect			0.14			0.11			4.52e-05
Treatments	2021	2022	2021+2022	2021	2022	2021+2022	2021	2022	2021+2022
B1	160.7a	229.0a	194.83a	273.7c	281.7a	277.7c	302.7abcd	278.7bc	290.7bc
B1N1	215.7a	213.0a	214.33a	461.0abc	383.7a	422.3abc	311.0abc	336.7abc	323.8abc
B1N2	266.3a	355.3a	310.834a	522.7ab	477.0a	499.8ab	360.7ab	410.3 abc	385.5ab
B1N3	288.7a	221.0a	246.57a	484.0ab	538.3a	511.2ab	282.0bcd	432.0abc	357.0abc
B2	175.0a	195.3a	185.17a	344.7bc	349.3a	347.0abc	225.0d	268.7c	246.8c
B2N1	205.0a	198.0a	201.50a	545.3a	362.3a	453.8abc	334.0ab	320.7abc	327.3abc
B2N2	182.7a	359.3a	271.00a	400.3abc	447.0a	423.7abc	286.7bcd	460.3ab	373.5abc
B2N3	302.3a	278.0a	290.17a	517.0ab	553.0a	529.0a	323.3abc	358.7abc	341.0abc
BA	226.3a	177.0a	201.67a	375.0abc	282.3a	328.7bc	249.0cd	291.0bc	270.0bc

C1N2	258.6a	335.7a	297.17a	524.7ab	372.7a	448.7abc	345.7ab	441.3abc	393.5ab
N2	209.3a	272.3a	240.83a	533.3ab	524.3a	528.83a	356.0ab	388.0abc	372.0abc
N3	283.0a	329.3a	306.17a	522.3ab	554.0a	538.2a	371.3a	479.3a	425.3a
Tukey HSD (0.05) main treatment effects	0.52	0.13	0.085	2.5e-04	0.10	2.43e-05	0.031	0.0016	2.27e-05
SD	84.1	98.2	92.2	102.8	142.9		60.5	87.0	
CV%	36.7	33.7	35.3	14.8			16.0	16.7	

B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha). Means with different letters under the same column are significantly different ($p<0.05$, TukeyHSD test)

4.3.2.2. Dry straw biomass

The pooled data on dry straw biomass for the two seasons indicated a highly significant differences between years for all the three growth stages (Table 8). But among treatments, significant differences were only observed at heading and ripening stages. No significant interaction between year and treatment was found (Table 8).

Specific year analysis revealed a non-significant effect of treatments on dry straw biomass in both 2021 and 2022 at the tillering stage (Table 9). However, significant variation was observed for both years at the heading stage. Treatments without N (B1, B2, BA) showed lower mean value for dry straw biomass compared to treatments with biochar and N combinations in 2021 which was similar to the trend observed in 2022 (Table 9). Further analysis revealed a non-significant variation in dry straw biomass among treatments in 2021 at rice ripening stage but significant treatment effect in 2022. The role of N addition to biochar in increasing dry straw biomass appeared less evident in 2021 which was in contrast to the observation made in year 2022.

Means separation after aggregating year one and year two data for dry straw biomass revealed higher dry straw biomass in second year than year one at among the growth stages (Table 9). Higher rice straw yield under the second season may be linked to the residual effect of biochar on the soil properties. Application of B1N3 resulted in highest dry straw biomass at tillering stage while lowest dry straw weight was recorded under B2. Furthermore, at heading stage, mean dry straw biomass significantly differed (Table 9). Lowest and highest means dry straw biomass were found under B1 and B1N2 respectively. Increase in N rates at the same biochar rates (B1N1, B1N2 and B1N3 or B2N1, B2N2 and B2N3) induced non-significant and non-linear progressive increase in dry rice straw biomass despite sharing different N and biochar rates. However, these increases were not significantly different compared to their respective N (N2 or N3) without biochar. Under medium N rate (N2), combination of high biochar with N (B2N2) produced lower dry rice straw biomass compared to either N2 or C1N2, indicating an inhibitory effect of biochar on dry straw weight at heading stage.

Overall, treatments without N (B1, B2, BA) tended to perform significantly poorer compared to those treatments with nitrogen application. This suggests that the improvement in dry rice straw weight performance under co-application of biochar and nitrogen fertiliser may be linked to nitrogen fertiliser effect and biochar-induced nutrient use efficiency which probably reduced nitrogen leaching.

At ripening stage, dry rice straw biomass varied significantly among treatments and year, with co-application and year two showing higher mean straw biomass than treatments without N and year one. Similar to our result, Shin et al. (2021) who revealed a non-significant difference in rice performance between treatment of high nitrogen application without biochar and treatment with low nitrogen and low biochar. Co-application of biochar and nitrogen increases nitrogen use efficiency (Kang et al., 2021; Liu et al., 2012) as claimed from this current study at ripening stage.

Table 8: ANOVA of rice dry straw biomass response to year and treatment applications at different rice growth stages during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire

		Tillering (g m^{-2})				Heading (g m^{-2})				Ripening (g m^{-2})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	6.47	3.24	4.76	0.013	332	166	0.038	0.96	15638	7819	0.31	0.74
Year (Y)	1	142.24	142.24	209.31	<2e-16	49502	49502	11.44	0.0015	1888240	1888240	73.64	4.18e-11
Treatment (T)	11	5.63	0.51	0.75	0.68	443587	40326	9.32	1.7e-8	1136872	103352	4.03	0.00038
Y x T	11	5.12	0.47	0.69	0.75	77624	7057	1.63	0.12	487132	44285	1.73	0.097
Error	46	31.26	0.68			198993	4326			1179596	25643		
Total	71	190.72	147.14			770038	101377			4707478	2069339		
SD			0.82				65.8				160.1		
CV			55.9				18.8				21.9		

SD: standard deviation, CV: coefficient of variation

Table 9: ANOVA of treatments and year effects on rice dry straw biomass (g m^{-2}) for three rice growth stages during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

Treatments	Tillering (g m^{-2})			Heading (g m^{-2})			Ripening (g m^{-2})		
Year 1			0.3b			316.8b			557.2b
Year 2			3.1a			369.2b			881.1a
Tukey HSD (0.05) main year effect			<2e-16			0.0015			4.18e-11
Treatments	2021	2022	2021+2022	2021	2022	2021+2022	2021	2022	2021+2022
B1	0.2a	2.7a	1.4a	177.6c	218.9c	198.23d	618.5a	588.5c	603.5abc
B1N1	0.3a	2.5a	1.4a	292.6bc	314.8abc	303.70abcd	441.3a	792.4abc	616.8abc
B1N2	0.3a	3.6a	2.0a	481.0a	400.6abc	440.82a	813.1a	1003.8abc	908.5a
B1N3	0.5a	2.9a	1.7a	402.3ab	460.6a	431.48a	612.3a	990.5abc	801.4ab
B2	0.2a	3.8a	2.0a	185.3c	264.7bc	225.02cd	340.2a	600.7c	470.5c
B2N1	0.3a	2.3a	1.3a	397.3ab	324.6abc	360.95abc	614.6a	859.2abc	736.9abc
B2N2	0.3a	3.6a	1.9a	291.7bc	427.2ab	359.43abc	590.9a	1144.6a	867.7ab
B2N3	0.4a	3.2a	1.8a	379.9ab	468.4a	424.18a	553.5a	953.6abc	753.6abc

BA	0.2a	2.5a	1.3a	190.7c	300.9abc	245.83bcd	434.0a	672.6bc	553.3bc
C1N2	0.4a	3.7a	2.0a	302.0abc	421.4ab	361.70abc	526.9a	1042.8ab	784.9abc
N2	0.2a	2.8a	1.5a	347.5abc	424.8ab	386.17ab	629.0a	853.6abc	741.3abc
N3	0.4a	3.8a	2.1a	353.5abc	403.9ab	378.70ab	512.6a	1071.3ab	792.0ab
Tukey HSD (0.05) main treatment effects	0.2	0.63	0.7	3.79e-05	0.00043	1.7e-8	0.2	0.00082	0.00038
SD	0.1	1.2	1.6	107.0	95.6	104.1	182.7	217.2	257.5
CV%	36.9	34.9	44.5	19.6	16.7	21.7	29.9	16.8	34.1

B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha + nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha). Means with different letters under the same column are significantly different ($p<0.05$, TukeyHSD test)

4.3.2.3. Dry root biomass

Analysis of variance of the two years data for dry root biomass revealed highly significant differences of dry root biomass between years for each of the three rice growth stages (Table 10). Further analysis of the performance of rice dry root biomass for individual years indicated statistical similarities among the treatments. Treatments application only significantly affected dry root biomass at tillering stage (Table 10) with B1N2 and C1N2 favouring root growth more than any other treatment when the two years data were pooled (Table 11). Statistically significant interaction was also found between year and treatment at the tillering stage.

At tillering stage, the mean weight of dry rice root was significantly higher in year two than year one (Table 11). But at both heading and ripening stages, year one showed higher mean rice dry root weight compared to year two. The higher mean dry root biomass found under year two at tillering stage may be attributed to the effect of biochar-induced progressive improvement in soil properties. However, no obvious reason can be adduced for the improvement in rice root weight in year one at heading and ripening growth stages.

In tandem to year effect, treatment application significantly affected the mean rice dry root biomass at tillering stage (Table 11). Highest mean dry root biomass was found under high N rate (N3) and lowest value was recorded under B1. In contrast, at heading stage, B1N3 arithmetically enhanced rice dry root while least value occurred under B1. Lowest mean dry root biomass was also found in treatment without N (B2) at the ripening stage while C1N2 non-significantly promoted dry root growth (Table 11). Similar significant increase in rice dry root weight after biochar application has also been documented (Ali et al., 2019). Contrary to our finding, Ali et al. (2022) assessed the effect of combined biochar and nitrogen fertiliser on rice morphological and physiological traits and reported that the application of biochar and nitrogen fertilizer significantly enhanced root traits. The difference between Ali et al. (2022) result and the result of the current study maybe due to the differences in properties of biochar or soil types used for these studies. Authors (Mukome and Parikh, 2015; Zhang et al. 2021) have noted that biochar produced from different feedstock have different properties and as such can impact soil functionality differently.

Table 10: ANOVA of rice root biomass response to year and treatment applications at different rice growth stages during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire

		Tillering (g m^{-2})				Heading (g m^{-2})				Ripening (g m^{-2})			
Factors	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	1.88	0.94	1.69	0.2	35877	17938	1.78	0.18	79389	39694	1.82	0.17
Year (Y)	1	65.95	65.95	118.24	2.65e-14	109996	109996	10.91	0.0019	215496	215496	9.9	0.0029
Treatment (T)	11	14.18	1.29	2.31	0.02	144665	13151	1.3	0.25	162465	14770	0.68	0.75
Y x T	11	11.53	1.05	1.88	7.00e-02	63940	5813	0.58	0.84	138900	12627	0.58	0.83
Error	46	25.66	0.56			463983	10087			1000887	21758		
Total	71	119.2	69.79			818461	156985			79389	39694	1.82	0.17
SD			0.7				100.4				147.5		
CV%			60.1				41.8				48.3		

SD: standard deviation, CV: coefficient of variation

Table 11: effects of treatments applications and year on rice dry root during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 and 2022 at the AfricaRice research field M‛be, Bouaké, Côte d'Ivoire

Treatments	Tillering (g m^{-2})			Heading (g m^{-2})			Ripening (g m^{-2})		
Year 1			0.5b			283.04a			365.03a
Year 2			2.4a			204.87b			255.61b
Tukey HSD (0.05) main year effect			2.65e-14			0.0019			0.0029
Treatments	2021	2022	2021+2022	2021	2022	2021+2022	2021	2022	2021+2022
B1	0.4a	1.6a	1.0cd	183.6a	175.5a	179.5a	403.5a	188.3a	295.9a
B1N1	0.8a	2.2a	1.5abcd	310.8a	157.8a	234.3a	438.5a	203.7a	321.1a
B1N2	0.6a	3.5a	2.0a	237.1a	143.3a	190.2a	322.6a	245.4a	284.0a
B1N3	0.4a	1.8a	1.1bcd	414.4a	214.3a	314.4a	422.4a	245.2a	333.8a
B2	0.3a	1.3a	0.8d	276.8a	155.4a	216.1a	315.8a	153.8a	234.8a
B2N1	0.5a	1.2a	0.9d	326.7a	204.4a	265.5a	311.4a	246.7a	279.1a
B2N2	0.5a	3.1a	1.8abc	255.3a	196.9a	226.1a	255.2a	316.6a	285.9a
B2N3	0.4a	2.7a	1.5abcd	317.3a	248.7a	283.0a	461.0a	262.5a	361.8a

BA	0.5a	1.7a	1.1bcd	225.5a	154.6a	190.0a	302.8a	174.9a	238.9a
C1N2	0.5a	3.6a	2.0a	304.3a	293.4a	298.9a	396.2a	372.9a	384.6a
N2	0.4a	3.2a	1.8abc	300.7a	294.4a	297.5a	366.1a	283.6a	324.9a
N3	0.7a	3.1a	1.9ab	243.9a	219.9a	231.9a	384.8a	373.8a	379.3a
Tukey HSD (0.05) main treatment effects	ns	ns	0.02	ns	ns	ns	ns	ns	ns
SD	0.2	1.2	1.3	113.0	86.5	107.4	142.6	138.3	150
CV%	47.2	42.2	48.9	40.8	42.0	38.9	40.3	39.6	34.9

B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha), ns = not significant. Means with different letters under the same column are significantly different ($p<0.05$, TukeyHSD test)

4.3.3. Biochar and N fertilization impact on temporal pattern of CH_4 flux

Temporal pattern of methane (CH_4) flux varied highly and significantly between dates of sampling, among treatments and with highly significant interaction between treatment and sampling dates (Table 4). Temporal pattern of CH_4 flux is presented (Figure 11). All treatments showed similar temporal pattern in CH_4 emission with strong variations in the amount of CH_4 produced. First CH_4 peak was observed ten days after seeding (DAS) under B2 and N3 treatments at seedling stage. These minor early CH_4 spikes observed in the single biochar, and high N treatments may be due to the degradation of the labile carbon (C) content of the biochar, and indigenous C content of the soil respectively (Kimani et al., 2020; Zhang et al., 2010). The fast mineralization of labile C of biochar can induce a short term increase in CH_4 emission under biochar application (Wu et al., 2019). Apart from these early spikes, the emissions of CH_4 from the various treatments maintained a gradual increase from the early seedling stage and peaked during the late vegetative stage. The second CH_4 peak occurred 60 DAS under C1N2 treatments which coincided with the panicle initiation period. From 60 DAS into the peak of the reproductive stage, CH_4 flux peaked for all the treatments, albeit with varying amplitudes. Among all the treatments, C1N2 as well as B1N3 and N3 showed strongest CH_4 fluxes at the late reproductive stage while low biochar with no N (B2 and B1) and low biochar and low N (B1N1, B2N1) inhibited temporal CH_4 flux.

The relatively low CH_4 emission observed for most of the treatments during the seedling stage can be attributed to poor aerenchyma tissues development at this stage. Rice aerenchyma tissue transports oxygen to the root tips in the rhizospheres and takes out CO_2, CH_4 and N_2O from the zone (Faseeh Iqbal et al., 2020; Conrad, 1993). Aerenchyma tissue is responsible for the transportation of more than 90% of the CH_4 emitted from rice paddy into the atmosphere (Bhattacharyya et al., 2016; Das and Baruah, 2008) which may have explained the high CH_4 emission observed at the later stage of rice growth. In our experiment, more than 80% of the observed CH_4 emission occurred from the late tillering stage when rice tillering had been completed and tissues well developed and established. Similar observation has been made by Zhong et al. (2016) who reported the peaking of CH_4 emissions mainly at the vegetative stage of rice growth. The final peak of CH_4 emission in our study occurred 103 DAS under high nitrogen application (N3).

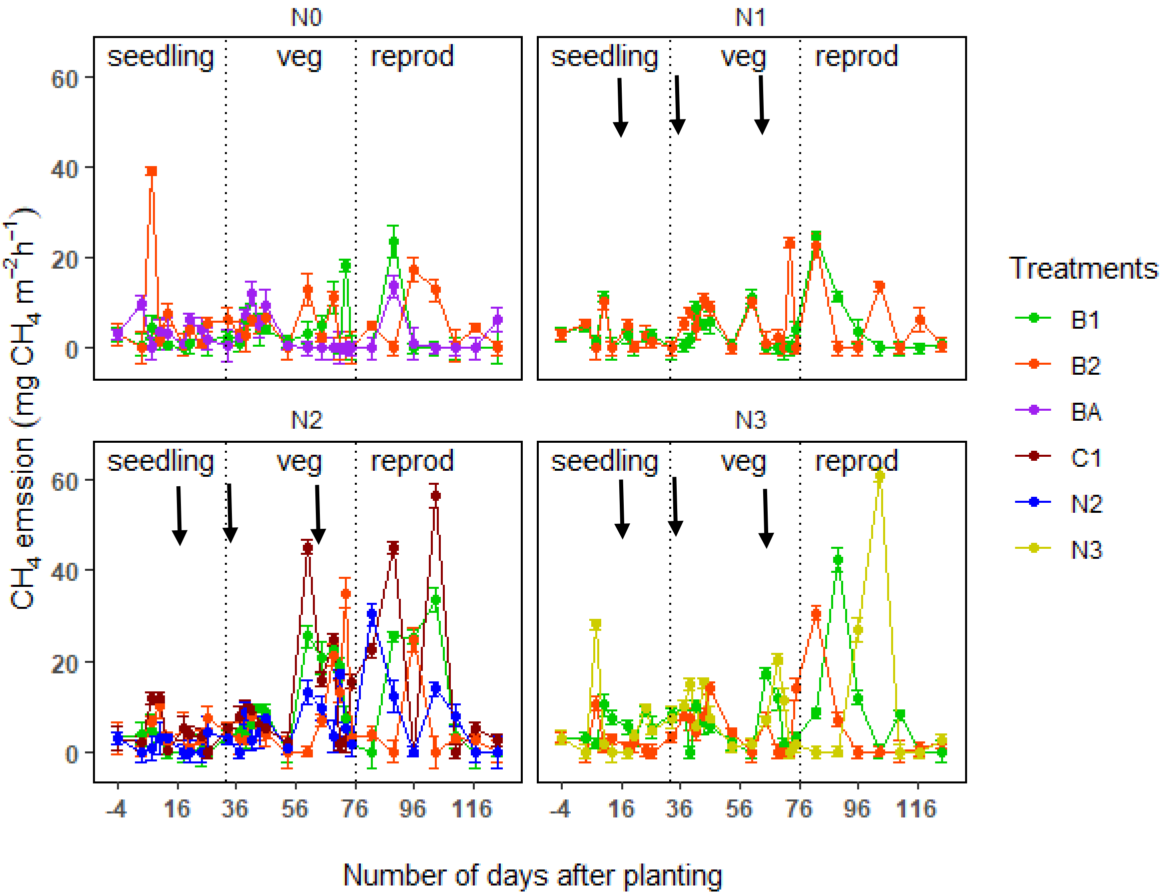


Figure 11: Effect of biochar and N fertilization on the temporal pattern of CH_4 flux during 2021 rice growing season. B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha).

Overall, biochar, cow dung, and nitrogen fertilization promoted CH_4 flux differently across the whole rice growing season (Figure 11). Biochar application appears to be the dominant factor regulating the temporal pattern of CH_4 flux. In the absence of biochar, CH_4 peaks were generally enhanced in both high and medium N rate. However, the addition of biochar decreased the amplitudes of the temporal CH_4 emissions. Most of the temporal CH_4 flux observed for all the treatments occurred during the reproductive stage of rice development. For treatment with biochar application, CH_4 flux started to decrease 96 DAS. Ye et al. (2019) claimed that sole nitrogen application lingered rice vegetative stage as observed in this study for treatments with sole high nitrogen application. Other authors (Sultana et al., 2021; Wei et al., 2015) have equally claimed that onset and rate of leaf senescence are regulated by nitrogen. Nitrogen availability delays senescence and hence modulates photosynthetic activities of leaves

(Zakari et al., 2021) including gas transportation from the root zone into the atmosphere and as such may have been responsible for the observed CH_4 emission persistence in our study. Our study supports these authors claims on nitrogen prolonging rice growth stage, thus CH_4 production by analogy.

As indicated by Figure 11, the temporal pattern of CH_4 emission was relatively low at rice seedling stage despite high soil moisture content at this stage (Figure 10). This shows that the effect of soil moisture on temporal CH_4 flux was overshadowed by the effects resulting from rice developmental stage. At seedling stage, rice aerenchyma tissues are yet to develop adequately and as such was unable to facilitate the transportation of CH_4 from the rhizosphere to the atmosphere. A regression analysis between soil moisture and temporal pattern of CH4 emission showed a weak but positive and highly significant relationship (Figure 12). The higher moisture content of the field only during the early stage may have contributed to the observed weak positive relationship between daily soil moisture and the temporal CH_4 flux (Figure 10). CH_4 gas is produced under anaerobic condition (Hasan, 2014; Reeburgh, 2003) and transported primarily to the atmosphere via rice plant's vascular tissues (Conrad, 1993). However, when plants are too small, CH_4 transportation to the atmosphere through these tissues is inhibited (Conrad, 1993).

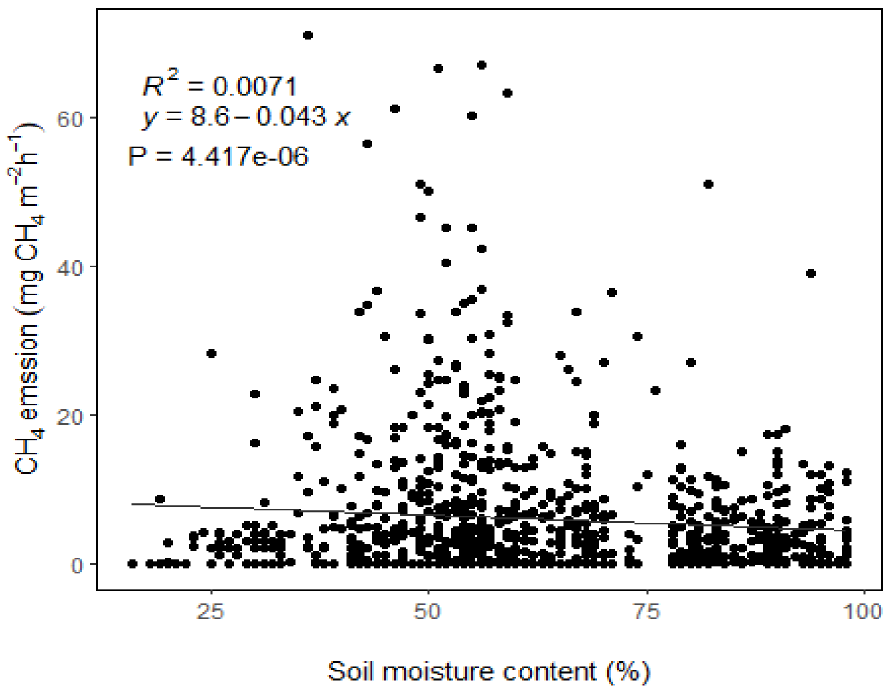


Figure 12: Response of CH_4 flux to field moisture regime during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

4.3.4. Temporal pattern of nitrous oxide (N_2O) emission under combined biochar and N-fertiliser application

Temporal pattern of Nitrous oxide (N_2O) emission from the investigated treatments is presented in Figure 13. There were highly significant effect of sampling dates and significant effect of treatments application along with highly significant interaction of dates of sampling and treatments on N_2O flux (Table 4).

R-squared (R^2) which is a statistical measure representing the proportion of the variance of a dependent variable that is explained by one or more independent variables in a regression model was shown (Figure 14) to be very weak ($R^2 = 0.02$). The independent variable (soil moisture) explained only 2% of the dependent variance (temporal pattern of N_2O emission) albeit highly significant (Figure 14). Several undetected factors are involved in predicting temporal pattern of N_2O flux.

Nitrous oxide (N_2O) is produced primarily by micro-organisms through the process of nitrification (oxidation of NH_4^+ to NO_3^-) and denitrification (reduction of NO_3^- to N_2O and N_2) (Takeda et al., 2021). Across treatments, N_2O emission was minimum during the peak of the rainy season (from -4 to 30 DAS) when the field was inundated and soil pore completely saturated with water but peaked during the dry season (from 56 DAS) (Figure 13). We speculate that the low moisture content of the field during the dry season encouraged the movement of oxygen into the soil which favoured microbial nitrification process, thus leading to high accumulation of NO_3^- and subsequent emission of N_2O (Wang et al., 2018). This was confirmed by the positive significant correlation observed between temporal N_2O emissions and soil moisture content (Figure 14)

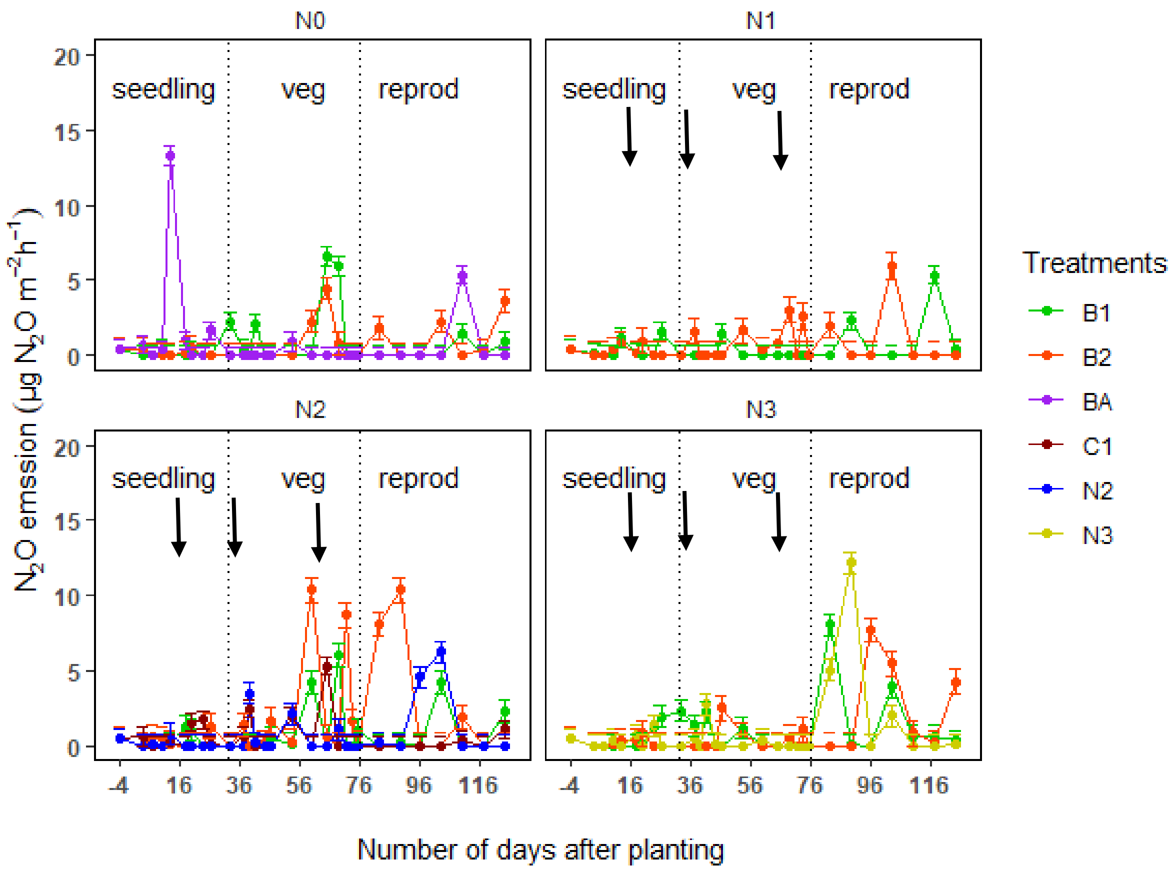


Figure 13: Temporal pattern of N_2O flux under different treatment applications during 2021 rice growing season. B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha).

On one hand, the amplitudes and days to highest amplitudes of N_2O emission differed among treatments. Early N_2O peak was observed 15 DAS from the BA treatment which is believed to be due to the fast degradation of the applied cow dung by the soil micro-organism (Figure 11) at seedling stage under no nitrogen. After this single peak, the pattern of emission took the same trajectory as other treatments. A rather more uniform peak was observed for all the N amended plots until 20 DAS which represented 4 days following fertilization. Similarly, other peaks were also observed on 39 (early vegetative stage) and 65 DAS (early reproductive stage) specially under N2 which coincided with six and three days after the first and second top dressing respectively. After these peaks, other non-uniform peaks were also observed at different dates for the different treatments which appear to be due to poor soil moisture distribution within the plots. As the field condition became drier, N_2O evolution gradually increased, with most of the treatments recording their maximum peaks (especially treatments with N2) from (52 DAS) at late vegetative stage. Increase in N_2O flux continued particularly for N2 treatments as the rainfall and soil moisture content of the field diminished until 115 DAS when the rice was harvested. Overall, biochar addition especially at 6 tons/ha with medium N (B2N2) and sole N2 application markedly promoted the temporal emission of N_2O at vegetative stage and reproductive while N3 tended to enhance N_2O emission at reproduction (Figure 11). Biochar application alters the processes of nitrification and denitrification through its action on NH_4^+ and NO_3^- availability in the soil (Nguyen et al., 2017) and by extension N_2O emission. Apart from NH_4^+ and NO_3^- availability, biochar also affects N_2O emission by regulating oxygen diffusion through soil profile by increasing soil water availability. Our finding is consistent with the results of (Chen et al., 2021; Liu et al., 2014) who noted that the temporal evolution of N_2O is mainly regulated by seasonal pattern with emission peaking during the dry season. Changing moisture regime resulted in changes in N cycle and thus increase in soil N_2O emission (Zhang et al., 2022). In confirming this finding, Shaaban et al. (2022) highlighted that decreasing soil moisture content to 60% water filled pore spaces resulted in increase in soil N_2O emission. The reported changes in N_2O emission pattern with varying soil water regimes indicated that soil moisture is a key driver regulating the temporal N_2O emission (Takeda et al., 2021).

On the other hand, under low or no N application, both low and high biochar strongly decreased temporal N_2O emissions. However, when N was combined with high biochar and N rate increased to 120 kgN/ha (B2N2), biochar mitigatory effect on N_2O was markedly decreased at seedling and vegetative stage and late season (Figure 10). It therefore appears that low quantity of biochar (B1N1, B1N2, B1N3) is more effective in decreasing the temporal soil N_2O emission. Also, the role of biochar in decreasing N_2O emission was more prominent in comparison to sole application of high N fertiliser (N3). Wang et al. (2018) reported that the application of high biochar resulted insignificantly enhanced N_2O emission compared to control of no biochar amendment. Increase in soil aeration due to biochar application can increase oxygen supply to the soil. High oxygen content reduces the ability of reductase to reduce N_2O to N_2, thereby resulting in higher N_2O emission (Shen et al., 2014). Similarly, the increased abundance of N substrate as biochar rate increased may have also contributed to the increased N_2O emission observed under higher biochar treatments (B2N1, B2N2, B2N3, B2). According to Kang et al. (2016), application of biochar in poor nutrient soil resulted in more than 60% reduction in N_2O emission while this reduction increased to about 63% under nutrient rich soil.

This report and our results suggest that N substrate availability is the main driving factor for N_2O evolution from soil. The combination of biochar and cow dung (BA) seemed to validate this point as the temporal N_2O emission peaked at the early plant growth stage the early stage. The easily degradable N content of cow dung which may have been readily available for microbial decomposition could have been responsible for the early N_2O peak. The combination of low biochar and cattle manure has been reported to cause more than 1.5 increase in N_2O emission relative to control (Romero et al., 2021). Additionally, in their meta-analysis, Shakoor et al. (2021) showed that the application of animal manure caused a significant increase in N_2O emission.

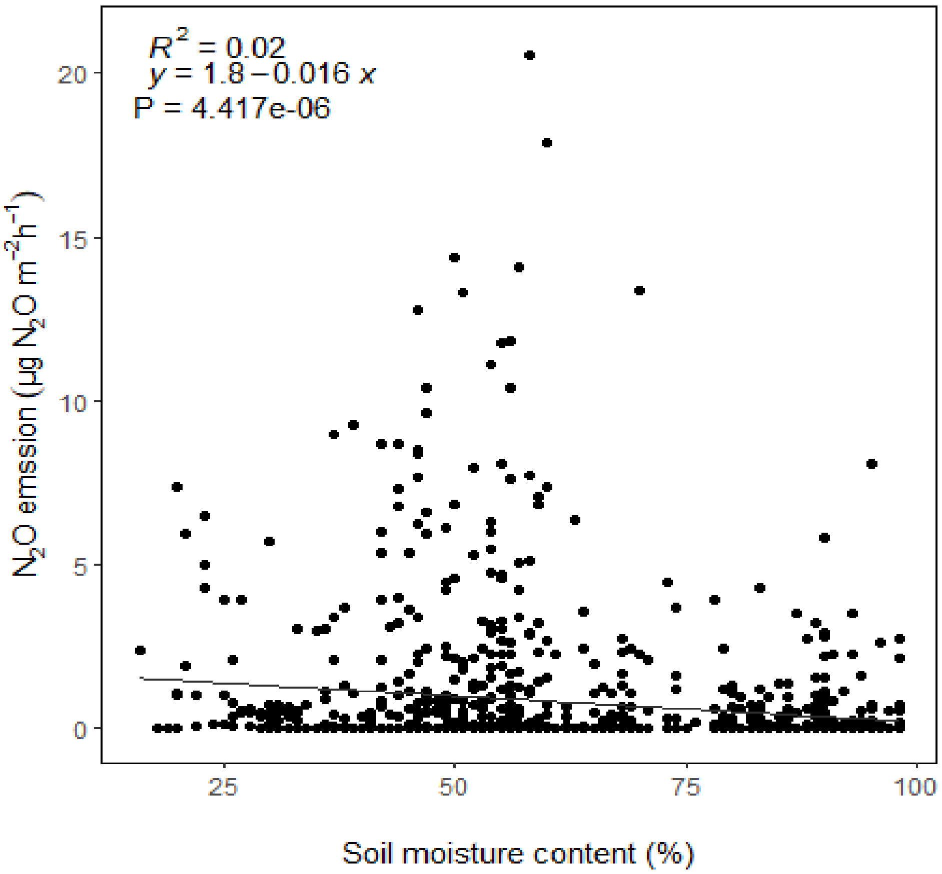


Figure 14: Effect of soil moisture regimes on temporal pattern of N_2O emission during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire..

4.3.5. Cumulative CH_4 and N_2O emissions, global warming potential (GWP), greenhouse gas intensity (GHGI), carbon sequestration potential and rice yield responses to biochar and N fertiliser application

4.3.5.1 Cumulative gas emission

Methane (CH_4) emission

Cumulative CH_4 emission varied highly and significantly among treatments (Table 12). Highest cumulative CH_4 emission, 195.04 kg/ha was recorded under the local farmers' management practice (C1N2, control) while the least CH_4 emission was found in BA (98.15 kg/ha) (Table 14). Treatments without nitrogen (N) fertiliser (B1, B2, and BA) distinctively decreased CH_4 emission compared to treatments with N. But in the absence of N, increase in biochar rate from 3t/ha to 6t/ha promoted the cumulative CH_4 emission probably due to increase in carbon (C) substrates for the activities of methanogens. Similarly, the addition of N fertiliser significantly enhanced the cumulative CH_4 emission whether as sole N or in combination with biochar (Table 14). Specifically, under low biochar and high N rate (B1N3), CH_4 emission was higher (10.6%) compared to high biochar and low N rate (B2N1). More so, the sole application of high N rate (N3) enhanced CH_4 emission (6.5% and 12.6% respectively) compared to co-application of high N with either low or high biochar (B1N3, B2N3). Compared to control (C1N2), B2N2, B2N3, B1N3, B1N1, B1N2, and B2N1 decreased the cumulative seasonal CH_4 emission by 18.63%, 22.00%, 17.46%, 29.86%, 35.61% and 29.47% respectively. This suggests that N fertiliser inclusion played a key role in regulating the cumulative emission of CH_4 than biochar. The high CH_4 emission under high N application could be attributed to the increase in the root biomass of rice and development of better aerenchyma tissue which favours the conduction of CH_4 from the root zone into the atmosphere (Sriphirom et al., 2021; Fang et al., 2021).

Alternatively, the interaction between biochar and N fertiliser may have played a critical role in the observed difference in different treatments. While the high cumulative CH_4 emission in C1N2 could be due to the exposure of the soil organic carbon to microbial decomposition by the hand hoe tillage effect. Under paddy field, no-tillage condition has been reported to inhibit CH_4 emission by as much as 23% (Maucieri et al., 2021). The inclusion of biochar significantly reduced the cumulative CH_4 emission compared to treatments without biochar. The decrease was however non-linear. According to Kim et al. (2017), the addition of biochar decreases methanogenesis by increasing soil aeration and oxygen availability within the rhizosphere which results in decrease in CH_4 emission. Also, the fixation of dissolved organic carbon by biochar decreases the available carbon to soil microbes which consequently decrease the cumulative CH_4 emissions (He et al., 2020). Additionally, biochar can induce increase in soil biodiversity and abundance of methanotrophic microbes which decreases CH_4 emission (Liu, et al., 2019; Wang et al., 2012). According to (Qi et al., 2021), co-application of biochar and N fertiliser decreases the cumulative CH_4 emission by decreasing *methyl coenzyme m reductase* (*mcrA*) gene abundances. Similar increase in CH_4 emission under high N rate has been found (Saiful et al., 2020; Zhou et al., 2018). The inhibitions of CH_4 emission under N application have also been reported (Yao et al. 2012; Lu et al., 2018). Varying soil, weather and biochar properties as well as different N sources and rates used by different researchers may be responsible for the differences in CH_4 emissions reported by different authors.

Although no linearly defined pattern can be established on the effect of N and biochar rate on the cumulative seasonal CH_4 emission, higher biochar and low N rate appeared more effective in mitigating the cumulative CH_4 emission in comparison to the control. Biochar high surface area as well as the promotion of the activities of the methanotrophs through increase in soil porosity may have contributed to the inhibition of CH_4 emission under biochar treatment. The recalcitrant nature of biochar which causes reduction in C mineralization (Thammasom et al., 2016) may have contributed to the low CH_4 emission observed under biochar treatments. It is therefore evident that biochar mitigated CH_4 flux compared to both N only treatment, and the control (C1N2).

Nitrous oxide (N_2O)

Cumulative N_2O emission was significantly affected by treatments applications (Table 12). Cumulative N_2O emission ranged from 0.48 kg/ha (B1) to 4.14 kg/ha (B2N2) (Table 14). B1, B2, and BA respectively inhibited N_2O emission by 83.69%, 61.27% and 54.13% compared to sole N treatment (N3) (Table 13). Low cumulative N_2O under sole or low biochar rates indicates that application of low rate of biochar as well as low biochar mixed with cow dung decreases N_2O emission. However, biochar inhibitory effect waned as biochar rate was increased or biochar is mixed with N. Higher cumulative N_2O emission with increasing biochar rate or inclusion of biochar suggests that the low N substrate and recalcitrant nature of biochar may have accounted for the low cumulative N_2O as found under B1 and B2 treatments. Another plausible explanation may be the adsorption of NH_4^+ and NO_3^- by biochar which limited N availability for nitrification and denitrification (Song et al., 2019**;** Ntinyari and Gweyi-onyango, 2021; Zhou et al., 2021). Relative to sole N_2 treatment, addition of B2 to N2 (B2N2) induced a strongly significant (75.18%) increase in the cumulative N_2O emission. But at a lower biochar rate with medium N (B1N2), the N_2O emission induced by increasing biochar diminished (1.83%) relative to N2 (Table 14). Compared to N2, C1N2 decreased N_2O emission by 41.18%. Demonstrating a complex interaction between biochar and soil ecosystem (Qian et al., 2014**;** Shen et al., 2014) as well as biochar and N fertiliser in N_2O emission. According to Lee et al. (2021) the varying N_2O emission associated with biochar application is due to biochar-induced complex interaction with soil under different experimental conditions.

Furthermore, biochar reduces the soil NO_3^- content which suppresses the process of denitrification and thus, inhibits N_2O emission (Aamer et al., 2021). Low bioavailability of biochar C can also lead to negative priming and hence decrease N_2O emission (Ntinyari and Gweyi-onyango, 2021). Another mechanism is the role of biochar in increasing soil pH which has been reported to decrease N_2O emission (Zhou et al., 2021). Biochar through carbonates is able to increase soil pH and gene abundance of nosZ (Aamer et al., 2021) which reduces N_2O to N_2 (Aamer et al., 2021; Kimani et al., 2020) and thus reduce cumulative N_2O emission. This has been re-emphasized by Žurovec et al., (2021) who reported a negative linear relationship between soil pH and cumulative N_2O emission from soil. Particularly, high biochar and N rates were critically important in enhancing the cumulative N_2O emission in the current study.

Overall, the effect of biochar differed under different N rates (Table 15). For instance, compared to sole N3 treatment, high biochar and high N rate (B2N3) marginally decreased N_2O emission by 1.25% while B1N3 decreased emission by 17.10% suggesting that the efficiency of biochar in decreasing cumulative N_2O emission is also related to the amount of nitrogen substrate available for the nitrifying and denitrifying bacteria (Gao et al., 2019). We infer that higher N rate induces a toxic environment for the bacteria (T. He et al., 2020) while at a very low N rate, insufficient N substrate is responsible for the reported low N_2O emission (Shen et al., 2014). There is therefore, the need to identity the optimum N and biochar rate that can guarantee lowest emission while ensuring maximum crop yield. Surprisingly, despite its low rate, combined application of biochar and animal manure (BA) stimulated higher N_2O emission (40.14%) than the co-application of biochar and N fertiliser (B1N1). This is likely due to the presence of easily biodegradable N and C content of the cow dung in BA as evidenced by its early N_2O peak (Figure 10). Relative to control (C1N2), co-application of either high biochar and high or low N rates (B2N3 or B2N1), or high N rate with low biochar (B1N3) significantly promoted N_2O emission by 5.8% to 111.8%. Albeit the increase was not linear. As the biochar and N fertiliser rates decreased, the stimulatory effect of biochar on N_2O emission diminished. Apart from the increase in soil aeration attributable to the effect of high biochar rate (B2N2 and B2N3), the increased availability of N substrate taking part in denitrification-nitrification process under high biochar and high N combination treatments may have also played significant role in the observed cumulative N_2O emission. This hypothesis was confirmed by the decrease in emission under low biochar and low N treatment (B1N1). Furthermore, the effect of tillage on soil properties and the microbial community structure especially the denitrifying bacteria may also be responsible for the low cumulative N_2O observed under control (C1N2) treatment. In a nine year study, Chen et al. (2021) demonstrated that no-tillage tended to increase the emission of N_2O from rice paddy which was attributed to greater soil compaction under no-tillage.

Global warming potential and greenhouse gas intensity

There were statistically significant differences ($p<0.05$) among treatments on global warming potential (GWP) (Table 12). GWP varied from 3.74 tCO_2-eqha^{-1} (B1) to 7.05 tCO_2-eq ha^{-1} (C1N2) (Table 14). Due to high dependence of GWP on CH_4 values (Equations 3), any treatment that recorded high CH_4 values will likely have high GWP. As such, C1N2 which emitted highest CH_4 amount contributed the largest GWP contrary to B1 and BA which emitted low CH_4 and N_2O.

Statistically significant effect of treatment on greenhouse gas emission intensity (GHGI) was found (Table 13). Greenhouse gas intensity (GHGI) varied from 0.85 tCO_2-eq ha-1/tgrain (B1) to 1.47 tCO_2-eqha-1/tgrain (C1N2) (Table 14). Since the values of GHGI are mainly determined by values of GWP and grain yield (equation 4), treatments with high GWP or high grain yield will mostly record high or low GHGI respectively. In this regard, apart from B1 and BA whose low GHGI values were due to low GWP, all other treatments (B2N3, B2N1, B1N2, B1N3) with low GHGI were due to high grain yield. Moreover, despite its high N_2O contribution, the GHGI of B2N3 was relatively low due to its high grain yield. This implies that to reduce GHGI, treatments with the capacity to increase rice yield should be encouraged as high yield neutralises the effect of GHGs emissions. Biochar played an important role in reducing GHGI, besides B2 treatment which produced low grain yield, all the biochar amended treatments reduced GHGI compared to both sole N treatments and control, indicating that biochar was effective in reducing GWP and by extension GHGI. According to Zhang et al. (2013), application of biochar at 20 t/ha and 40 t/ha exerted strong reductive effect on GWP. Our finding is consistent with the report of Wu et al. (2019) who reported a significant decrease in GWP in combined application of biochar and N fertiliser. However, the mechanism of this positive effect is dependent on soil condition. Biochars liming effect and improvement in soil properties which promoted crop yield is hypothesised to be responsible for the reduction in GHGI under biochar application (Liu et al., 2019). Increase in nutrient use efficiency particularly N associated with biochar use, resulted in decrease in N_2O emission. Furthermore, a biochar-induced decrease in GHGI relative to sole N fertiliser application has been reported by Shi et al., (2022) and Ma et al. (2019). Similar observation has also been expressed by Liu et al. (2019) who noted a non-significant effect of biochar on GHGI in the absence of N fertiliser. Although it enhanced rice yield, the high CH_4 emission under high (180 kgN/ha) and medium N rates (120 kgN/ha) neutralized the positive impact of N on yield and thus resulted in high GHGI. This contradicted the finding of Guo et al. (2022) who reported a significant decrease in GHGI under N application.

Carbon sequestration

Highly significant differences among treatments on the amount of carbon sequestered (C_Seq) in the soil after a single rice growing season were found (Table 13). Carbon sequestration ranged from -0.68 (C1N2) to 5.02 kg ha^{-1} (B2N2) (Table 14). Biochar treatment consistently improved the soil ability to sequester carbon. B2N3 sequestered highest amount of carbon while the lowest rate of sequestered carbon was observed under C1N2. The low degradability of biochar C ensured that part of the C in the applied biochar remains in the soil beyond a growing season (Han et al., 2022; Lehmann et al., 2006). Geng et al. (2022) reported that biochar boosters carbon sequestration in the soil by shielding the indigenous carbon from microbial mineralization and reduction in the proportion of mineral-bonded organic carbon. Apart from the reduced C degradation associated with biochar, co-application of biochar and N may have enhanced the diversion of photosynthetic metabolites into the root region which encouraged root growth and thus increased carbon sequestration within the rhizosphere (Ali et al., 2015). Higher biochar rate and N tendered to promote carbon sequestration when applied together. However, sole application of either biochar or N was even at high rates were not as effective as their co-application in sequestering carbon. Similar to our finding, high sequestration of C within the root and rhizodeposit of rice under co-application of biochar and N fertiliser than sole N application has been reported by Qi et al., (2020).

Tillage by hand hoeing (C1N2) enhanced C loss from the field (Table 14). Compared to N3, high biochar with high N rate (B2N3) increased soil carbon content by more than 200%. while relative to control (C1N2), B2N2 enhanced carbon sequestration by more than 800%. This high increase of C under biochar application demonstrated that combined application of biochar and N fertiliser has a great potential to improve soil productivity and mitigate greenhouse gas emission from rice field.

Furthermore, Shin et al. (2019) estimated that co-application of biochar and pig manure resulted in 2.3 times increase in carbon sequestration compared to control. While more than 15% increase in soil organic carbon following biochar application has also been reported by Shi et al. (2022). Biochar and non-tillage may have also reduced soil respiration which ultimately led to the conservation of soil organic matter. The negative sequestration as seen with the control treatment implies that soil respiration and C loss from the soil outweighed biomass return. This carbon loss suggests that tillage and sole N application exposed the soil C to air and micro-organisms and as such enhanced soil respiration and GHGs emission.

Many researchers (Wu et al., 2019**;** Koyama et al., 2015; Wang et al., 2018) have reported a significant increase in C sequestration under co-application of biochar and N compared to N alone. Carbon sequestration and other benefits associated with biochar application to soil re-emphasize the need to continuously promote biochar utilization for crop production. It is also exciting to note that in the current era of climate variability and change and carbon trading, carbon sequestration through biochar application can become an important source of additional revenue to subsistent farmers. For instance, the profit analysis for a single rice growing season using combined nutrient approach with biochar is estimated at $145.59 per hectare (Shin et al., 2019).

Table 12: ANOVA of cumulative CH_4 (TCH_4), N_2O (TN_2O) and GWP under different treatments applications during the study of biochar and N-fertilization effects on GHGs emissions and productivity of lowland rice conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

		TCH_4 (mg m^{-2} hr^{-1})				TN_2O (µg m^{-2} hr^{-1})				GWP (tCO_2-eq ha^{-1})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	532	266	0.58	0.57	4.03	2.01	3	0.07	1.8	0.9	1.66	0.21
Treatment (T)	11	28619	2602	5.64	0.00029	35.76	3.25	4.84	0.00083	46.19	4.2	7.72	2.72e-05
Error	22	10143	461			14.79	0.67			11.97	0.54		
Total	35	39294	3329			54.58	5.93			59.96	5.64		
SD			21.5				0.8				0.7		
CV%			14.5				44.4				13.7		

SD; standard deviation, CV; coefficient of variation

Table 13: ANOVA of carbon sequestration (C_Seq) and greenhouse gas intensity (GHGI) under different treatments applications during the study of biochar and N-fertilization effects on GHGs emissions and productivity of lowland rice conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

		GHGI (tCO_2-eq ha^{-1}/tgrain)				C_Seq (kg C ha^{-1})			
Source of variation	DF	SS	MS	F	P	SS	MS	F	P
Rep	2	0.31	0.16	3.15	0.063	15.58	7.79	3.79	0.04
Treatment (T)	11	1.44	0.13	2.67	0.02	88.05	8.01	3.88	0.0033
Error	22	1.09	0.05			45.43	2.07		
Total	35	2.84	0.34			149.06	17.87		
SD			0.22				1.4		
CV%			21.1				94.7		

SD: standard deviation, CV: coefficient

Table 14: cumulative seasonal CH_4 and N_2O emissions, GWP, GHGI and sequestered carbon during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

Trt	TCH_4 (kg/ha)	TN_2O (kg/ha)	GWP (tCO_2-eq/ha)	GHGI (tCO_2-eqha^{-1}/tgrain)	Paddy yield (ton/ha)	C_Seq (Mg/ha)
B2N3	152.14bcde	2.91 ab	6.04ab	0.94bc	6.48a	4.82a
B2N1	137.57cdef	1.47ab	5.12abc	0.87c	5.91a	1. ab
B2N2	158.70bcde	4.14a	6.63ab	1.18ab	5.78ab	5.02a
B1N3	160.99abcd	2.44ab	6.20ab	1.08ab	5.77ab	1.33ab
N3	171.38abc	2.94ab	6.70a	1.24ab	5.42ab	1.26ab
B1N2	125.59bcd	2.32ab	4.96abc	0.95bc	5.24abc	1.39ab
B1N1	136.81cdef	0.96b	4.94abc	1.02bc	4.99bc	1.08ab
N2	179.86ab	2.20ab	6.82ab	1.38ab	4.94bc	0.54ab
C1N2	195.04a	1.39ab	7.05a	1.47a	4.81bc	-0.68b
BA	98.15g	1.35ab	3.74c	0.93bc	4.44bc	0.91ab
B1	105.71fg	0.48b	3.74 c	0.85c	4.43bc	1.33ab
B2	125.07efg	1.14ab	4.59 bc	1.28ab	3.62c	1.59ab

Note: Trt: treatment, C_seq: sequestered carbon, TCH_4: cumulative CH4, TN_2O: cumulative N2O, B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha). Means with different letters under the same column are significantly different ($p<0.05$, TukeyHSD test).

4.3.6. Effects of biochar and N-fertiliser application on rice grain yield and harvest index

Paddy yield

Year and treatments application significantly affected rice yield (Table 15) but not interaction between treatment and year. Treatment effects on rice grain yield during the two seasons were generally similar for most of the treatment groups (Figure 15).

In 2021 rice yield ranged from 3.62 t/ha (B2) lowest to 6.48 t/ha (B2N3) highest and were significantly affected by biochar and N fertilization (Figure 15). The average rice yields were significantly higher under treatments with co-application of biochar and N fertilizer (B1N1, B1N2, B1N3, B2N1, B2N2, and B2N3) than under the treatments of either sole biochar (B1, B2) or N fertiliser (N2, N3) or biochar and cow dung (BA) (Figure 15). Relative to the control (C1N2), co-application of biochar and N fertiliser enhanced rice grain yield by between 3.74% and 34.72%. High rate of biochar and high N fertiliser (B2N3) produced the highest yield compared to the control. Sole application of high biochar (B2) inhibited rice yield. In the absence of additional source of nitrogen, high rate of biochar to a soil with low indigenous nitrogen can significantly impair crop yield (Qin et al., 2016) by limiting N supply to crops.

Table 15: ANOVA of rice yield and harvest index under year and treatments applications during the study of biochar and N-fertilization effects on GHGs emissions and productivity of lowland rice conducted in 2021 and 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

		Rice yield (t ha^{-1})				Harvest index (%)			
Factors	Df	SS	MS	F	P	SS	MS	F	P
Rep	2	4.51	2.26	5.19	0.0093	196.7	98.3	2.35	0.11
Year (Y)	1	3.12	3.12	7.18	0.01	486.3	486.3	11.6	0.0014
Treatment (T)	11	40.37	3.67	8.44	7.09e-08	326.5	29.7	0.71	0.72
Y x T	11	6.8	0.62	1.42	0.2	344.3	31.3	0.75	0.69
Error	46	20.01	0.44			1928.8	41.9	41.9	
Total	71	74.81	10.11			3282.6	687.5		
SD			0.7				6.5		
CV%			13.3				19.1		

In 2022 season, responses of rice yield to treatment application were significant (Figure 15). Yield varied from 3.63 ton/ha (B1) minimum to 6.55 ton/ha (B1N3) maximum. High N rates applied singly or in combination with biochar promoted rice yield than sole low N application. Irrespective of combination rates, application of biochar with N fertiliser engendered more positive response than sole biochar application. Specifically, B1N3, and B2N3 greatly promoted rice yield than either B1, B2, and BA. Relative to control (C1N2), B1N3 enhanced rice yield by 16 % while B1 caused a 24.2% decrease in yield. Additionally, high sole N application (N3) decreased rice yield by 4.5% and 10.3% compared to B1N3 and B2N3 respectively.

Overall, higher rice performance was observed under combined application of biochar and N fertiliser for the two rice growing seasons. This may be attributed to higher nutrients retention (Wei et al., 2019), carbon sequestration (Yin et al., 2021) and improved N uptake by plant (Sánchez-García et al., 2020) induced by biochar. Surprisingly, in 2021, high rate of biochar and low N (B2N1) increased rice yield (22.87%) more than those produced by high N rates with low biochar rates (B1N2 and B1N3) at 8.94% and 19.96% compared to the control. Also, under the same biochar rate, increasing N application from 60 kgN/ha to 120 kg N/ha did not significantly increase rice yield. And, increasing biochar rate and decreasing N rate produced similar effect on yield as decreasing biochar rate and increasing N rate. Additionally, low biochar rate applied in combination with either low or medium N rates produced similar yield effect as high sole N application rate. Higher N availability in individual treatment generally favoured rice grain yield. Regardless of nitrogen or biochar rates, co-application of N and biochar non-significantly promoted rice yield. Except for B1, B2, BA and B1N1, all other treatment combinations produced similar grain yields during the 2022 rice growing season.

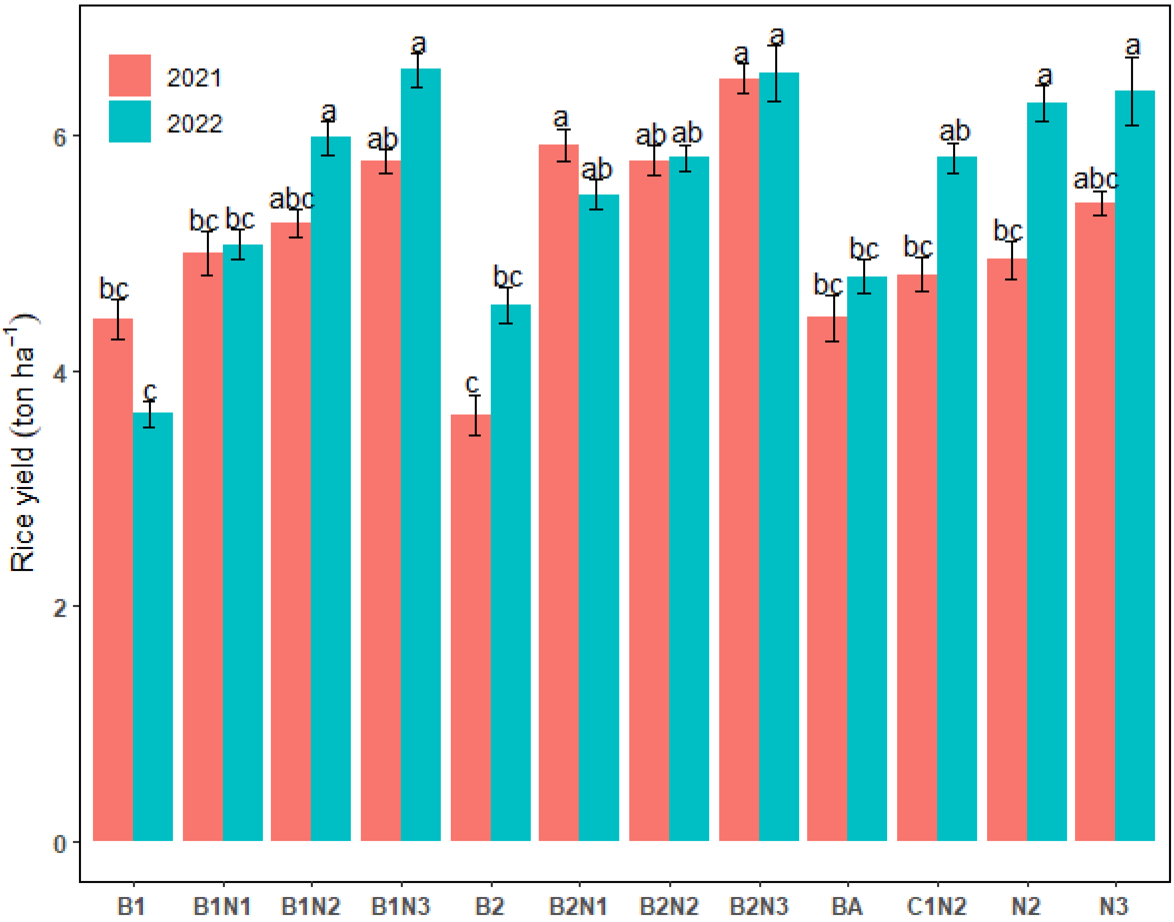


Figure 15: Treatment effects on rice grain yield during the 2021 and 2022 growing seasons. B1 (Biochar: 3t/ha), B1N1(biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha). Means are separated per year and bars with different letters are significantly different ($p<0.05$, TukeyHSD test).

Another probable explanation for the observed increase in rice yield under co-application of biochar and N fertiliser over single application of either biochar or N include: release of cations and prevention of N loss through volatilization by biochar (Phares and Akaba, 2022), improvement in soil physico-chemical properties (Nguyen et al., 2021; Elias et al., 2020) and increase in N availability and use efficiency (Abbruzzini et al., 2019). Other pathways through which biochar application improves crop yield include serving as a direct source of essential micro and macro-nutrients, nutrient (Lashari et al., 2015). The large surface area and high CEC of biochar are also able to attract and retain nutrients especially NH_4^+ for plants uptake and prevents its leaching from the soil.

Activation of biochar with cow dung (BA) and the sole application of biochar both at high and low rates (B1 and B2) were not effective in promoting rice yield. These treatments (BA, B1 and B2) decreased rice yield by 7.69%, 7.90% and 24.74% respectively compared to the control (C1N2) in 2021 growing season. Consistent to 2021 yield result, BA, B1 and B2 also decreased yield by 5.3%, 28.4% and 10.3% respectively compared C1N2 The observed decrease may be related to the inability of these treatments to supply sufficient nutrients to meet the crop nitrogen and other nutrients requirements. Our result contradicted the finding of Phares and Akaba (2022) who reported increase in rice yield under biochar and application of organic manure derived from the compost of poultry manure and elephant grass. This contradiction may be related to biochar application rate and source of the organic matter. It can also be explained by the short term impact of biochar on soil properties (Bass et al., 2016), initial nutrient status of the soil (Crane-droesch et al., 2017), and the dependence of biochar properties on its feedstock (Wei et al., 2019). Our results appears to support that biochar increases rice yield but immobilizes soil inorganic N at high biochar rate and low N. Elias et al. (2020) revealed that co-application of biochar with N results in decrease in inorganic N and the reduction increased with biochar rate. It is important to note that single application of either N or B was unable to march the positive rice yield obtained under their co-application. This clearly justifies the efforts in encouraging biochar use with N fertiliser. Therefore, for optimum performance, biochar should always be applied with N fertiliser as it appears that biochars positive impact is better expressed in the presence of N fertiliser.

Furthermore, compared to their corresponding treatment in 2021, rice yield was generally higher in 2022 season (Figure 15). The residual effect of biochar application may have contributed to this observed increase. In a multi-year experiment, Qin et al. (2016) revealed a successive increase in rice yield following yearly biochar application. Consistent to our finding, (Nan, wang, et al., 2020) has also demonstrated that successive return of biochar to the field can play a significant role in improving yearly rice output from the field. According (Liu et al., 2021), long-term biochar application to soil improves soil bulk density as well other soil properties which favours crop yield. Biochar application can also trigger additional nutrients supply to the soil which could be responsible for the observed increase in rice yield following biochar application (Nan, wang, et al., 2020)

Rice harvest index was significantly affected by year but was not significantly by treatment application and interaction between treatment and year (Table 15).

In 2021, harvest index ranged from 31.7% (B1) to 41.3% (N2) (Figure 14). Progressively increasing nitrogen rates applied with biochar (ie B1N1, B1N2, B1N3 and B2N1, B2N2, B2N3) non-linearly decreased harvest index. In 2021 growing season, the decrease in harvest index with increasing N application was more observable under high biochar rate (B2) besides B2N3. Similar pattern of treatment effect on harvest index was also observed during the 2022 rice growing season. In 2022, highest value of harvest index (38.4%) was found in N2 treatment whereas lowest value (26.5%) was recorded in N3. Among the years, higher average harvest index was recorded during 2021 growing season compared to 2022 (Figure 16) while across treatments and years, maximum harvest index was recorded under N2 (39.9%), and lowest value under B2N2 (31.1%). Overall, particularly in 2021 rice season, absence of biochar under medium N fertilization (120 kgN ha^{-1}) marginally enhanced harvest index, just as sole biochar or biochar application with cow (Figure 16). But high N application decreases harvest index. Similar to our finding, (Qin et al., 2016) indicated that biochar application enhances rice harvest index while negative correlations have been reported between nitrogen application and harvest index (Tao et al., 2022; Gos, 1997). High N fertilization in rice causes delay in senescence which slows the grain-filing period and thus results in decrease in harvest index (Unkovich et al., 2010).

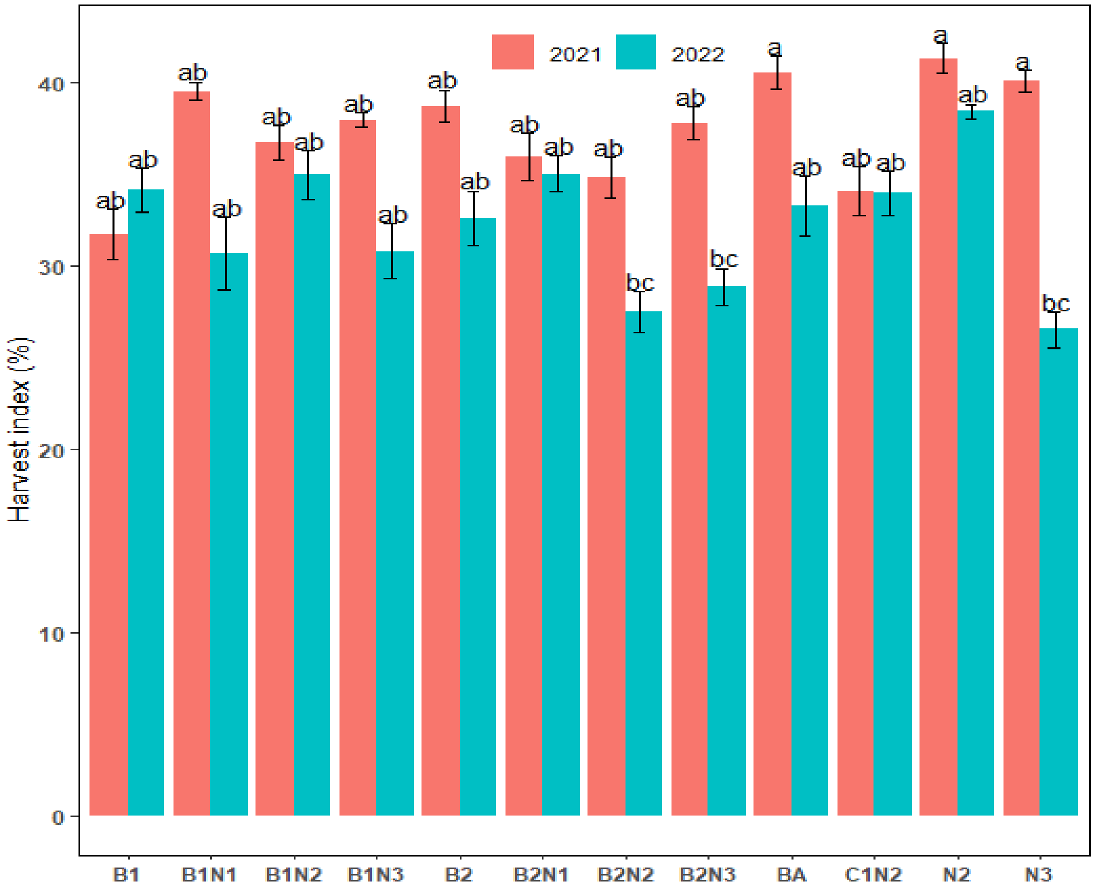


Figure 16: Treatment effects on rice harvest index during the 2021 and 2022 rice growing seasons. B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha). Means are separated per year and bars with different letters are significantly different ($p<0.05$, TukeyHSD test).

4.3.7. Regression of rice morphological traits, yield and greenhouse gas emissions

4.3.7.1. Relationship between morphological traits and greenhouse gas emission at tillering stage

Results of regression analyses among tiller numbers, dry root weight and dry straw weight on greenhouse gas emission at the rice tillering stage are presented (Figure 17). Results (Figure 17) indicated a poor positive but non-significant relationship between number of rice tillers and CH_4 emission (R^2=3%), dry straw weight and CH_4 emission (R^2=5%), and dry root weight and CH_4 emissions (R^2=9%). Similar relationship was also observed between rice tiller numbers and N_2O (R^2=2%), rice dry straw weight and N_2O (R^2=20%), and dry root weight and N_2O

(R^2=1%). Neither the variation in N_2O nor CH_4 emission could be well explained by rice morphological traits at the early rice tillering growth stage (GS1). A possible explanation could be the small size of rice aerenchyma tissues at this stage which may imply low contribution to emission processes or may have allowed other environmental processes dominate their contributions.

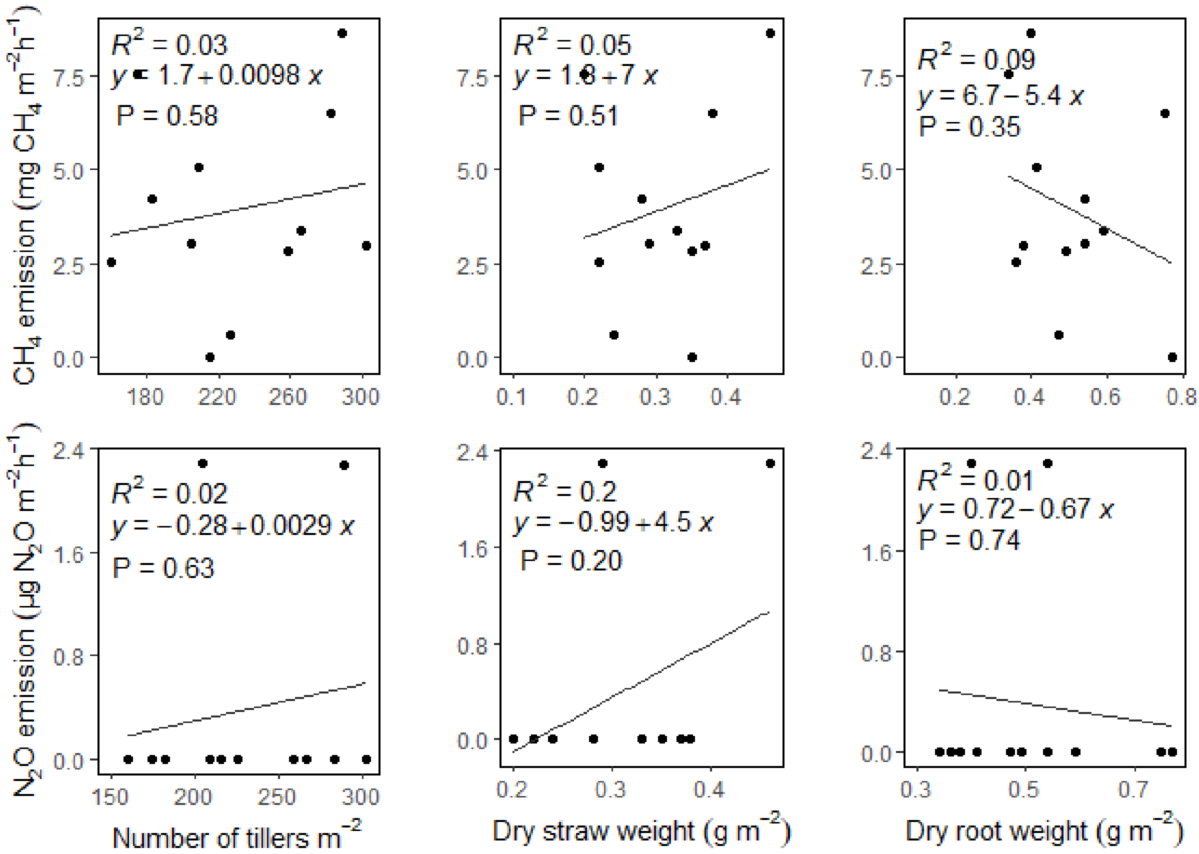


Figure 17: Regression of rice morphological traits and greenhouse gases emission at the rice tillering growth stage (GS1) under different treatment applications during the 2021 rice growing season.

4.3.7.2. Relationship between morphological traits and greenhouse gas emission at heading

As could be seen at the later rice growth stage (Figure 18), the effect of rice morphological parameters became more apparent as the rice growth advanced. Particularly at the heading stage, rice dry straw weight showed a highly significant positive relationship with both CH_4 and N_2O emissions. Although the coefficients of determination were fairly strong and weak for CH_4 and N_2O respectively. Equally, rice tiller numbers and dry root weight showed positive but non-significant relationship to both CH_4 and N_2O with weak coefficients of determination (Figure 18).

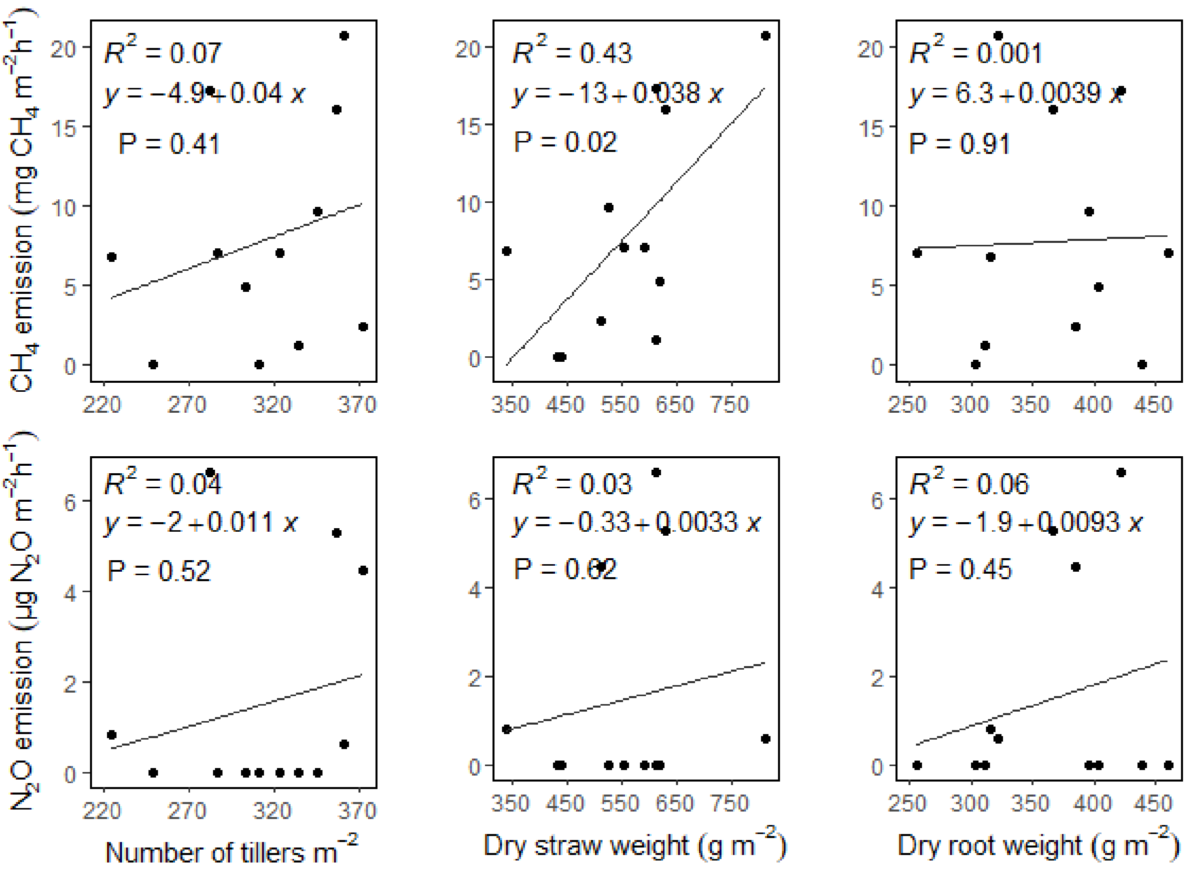


Figure 18: Regression of rice morphological traits and greenhouse gases emission at heading growth stage (GS2) under different treatment application during the 2021 season.

4.3.7.3. Relationship between morphological traits and greenhouse gas emission ripening stage

Similar to tillering and heading growth stages, at the ripening stage, weak and positive relationships were observed between all the rice morphological traits and GHGs emissions (Figure 19). For all the rice growth stages, aside the significant positive relationship between GHGs and rice dry straw found at ripening growth stage, all rice traits largely showed weak and non-significant positive relations with GHGs emissions.

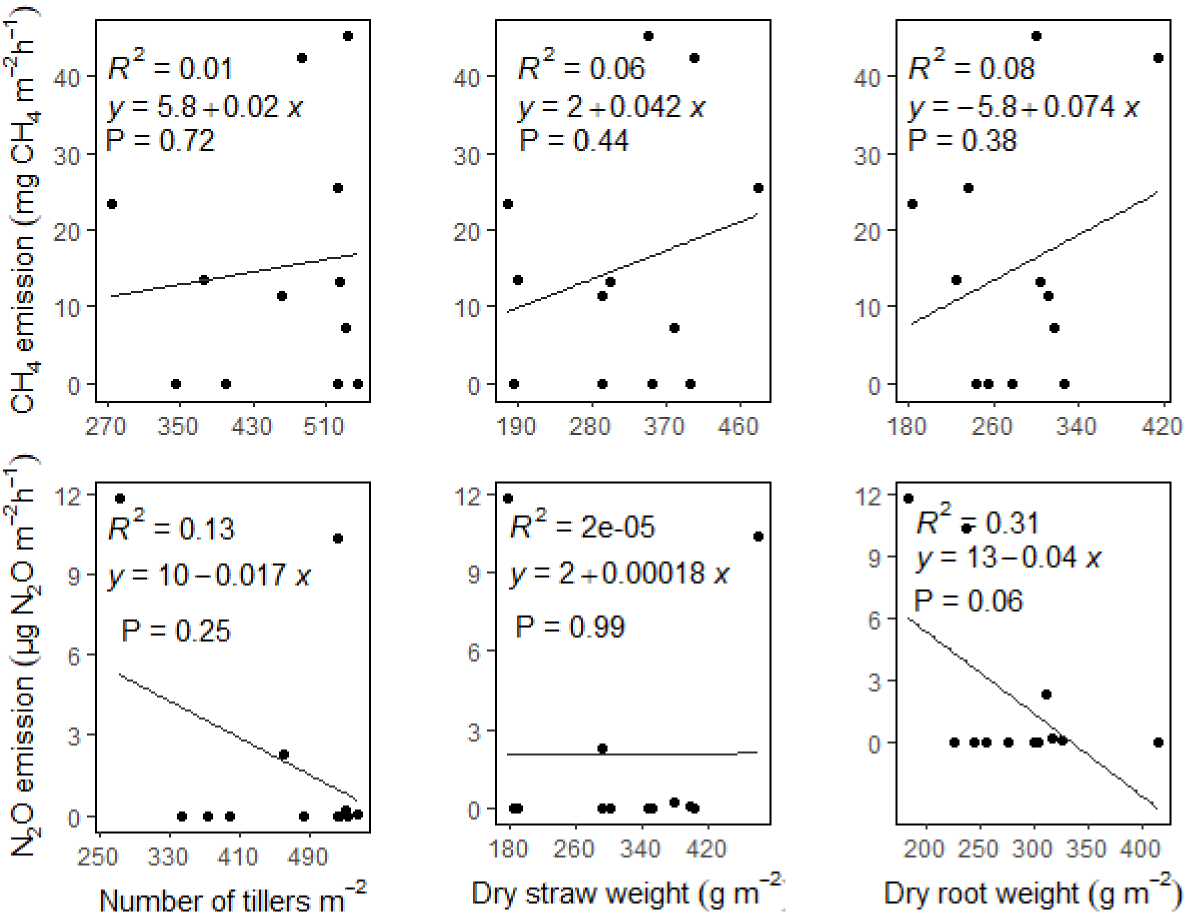


Figure 19: Relationship of rice morphological traits and greenhouse gases emission at ripening growth stage (GS3) under different treatments applications during the 2021 rice growing season.

Increase in rice root favours the microbial decomposition of dead roots within the rhizosphere which promotes the emission of GHGs. Since aerenchyma tissue is a function of rice tillers and straw, by extension increase in rice tillers result increase in GHGs emissions (Faseeh Iqbal et al., 2020). Result from this study is consistent with the finding of Setyanto et al. (2016) who reported positive correlation between rice tillers number and CH_4 emission from rice field. Strong relationship between number of tillers and CH_4 emission suggests that rice variety with lower number of tillers could potentially decrease CH_4 emission from rice field. Contrary to our finding, Zhang et al. (2019) have reported a strong negative correlation between rice root weight and greenhouse gas emission from rice field. While Zhang et al. (2015) have opined that above ground morphological properties of rice are poor predictors of CH_4 emission from rice field.

4.3.7.4. Relationship between morphological traits and rice yield at tillering

Figure 20 showed the relationship among rice morphological traits (dry straw weight, dry root weight and number of tillers) and rice paddy yield at the tillering stage. Tiller number and dry straw weight both showed strong positive correlation with rice paddy yield while weak positive relationship was found between rice yield and dry root weight. The relationship between rice yield and rice straw was significant ($p<0.05$) whereas no significance differences were found for both tiller numbers and dry root weight at the rice tillering stage.

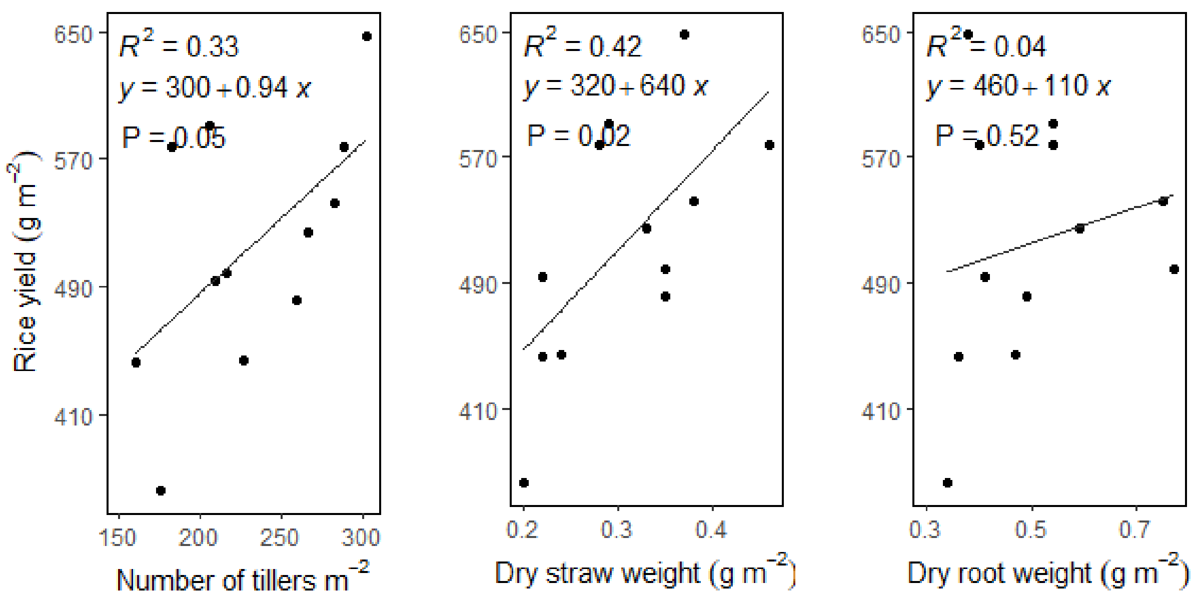


Figure 20: Relationship between rice yield and rice morphological traits at tillering stage during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire

4.3.7.5. Relationship of morphological traits and rice yield at heading

Relationship between rice morphological traits and rice yields were similarly weak and positive with no significant differences at the heading stage (Figure 21) and ripening stage (Figure 22). Albeit, rice tiller numbers and rice straw both showed stronger positive relationship compared to rice dry root (Figures 21).

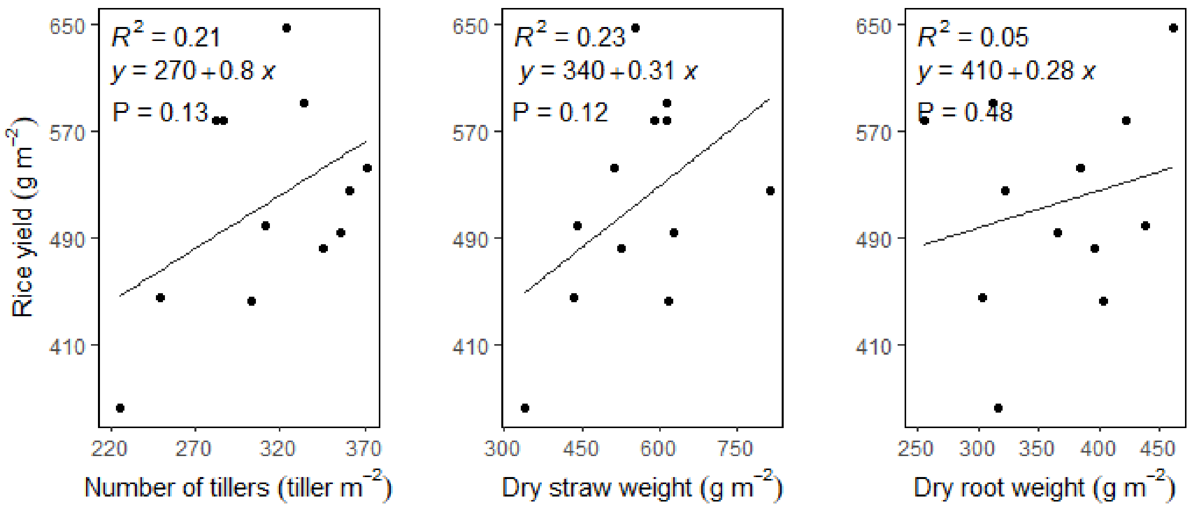


Figure 21: Relationship between rice yield and rice morphological traits at heading stage under different treatment applications during the 2021 and 2022 rice growing season.

4.3.7.6. Relationship of morphological traits and rice yield at maturity

Rice tiller numbers, straw and roots are important traits necessary for enhancement of rice yield. The roots are important for nutrient extraction from the soil while straw houses the leaves and are responsible for photosynthetic activities. Tiller numbers are also related to the yield as higher number of tillers portends higher number of panicles and by extension increase in grain yield. Increase in rice roots implies increase in nutrient extraction and improvement in rice performance.

Beside nutrients and water acquisition from soil (Fang et al., 2021), root biomass is also important for achieving more panicle number, more spikelets per panicle as well as greater grain-filling percentage which consequently leads to increase in yield (chang Yang et al., 2012). Also, dry straw which is a component of number of tillers is also critical for rice yield. Hence increase in number of tillers does not just increase the potential number of panicles both also the potential for sun light utilisation which favours rice performances in the field. To further emphasize the role of tiller on yield, (Sharma, 1995) investigated the relationship between tiller mortality and wheat yield and found that decrease in tiller numbers through mortality resulted in more than proportionate decrease in yield. Inadequacy of tillers, root biomass and straw can hugely limit rice yield by truncating photosynthate allocation. It was therefore expected as was observed in our study that as the tiller numbers, dry straw and root biomass increased that rice yield should increase.

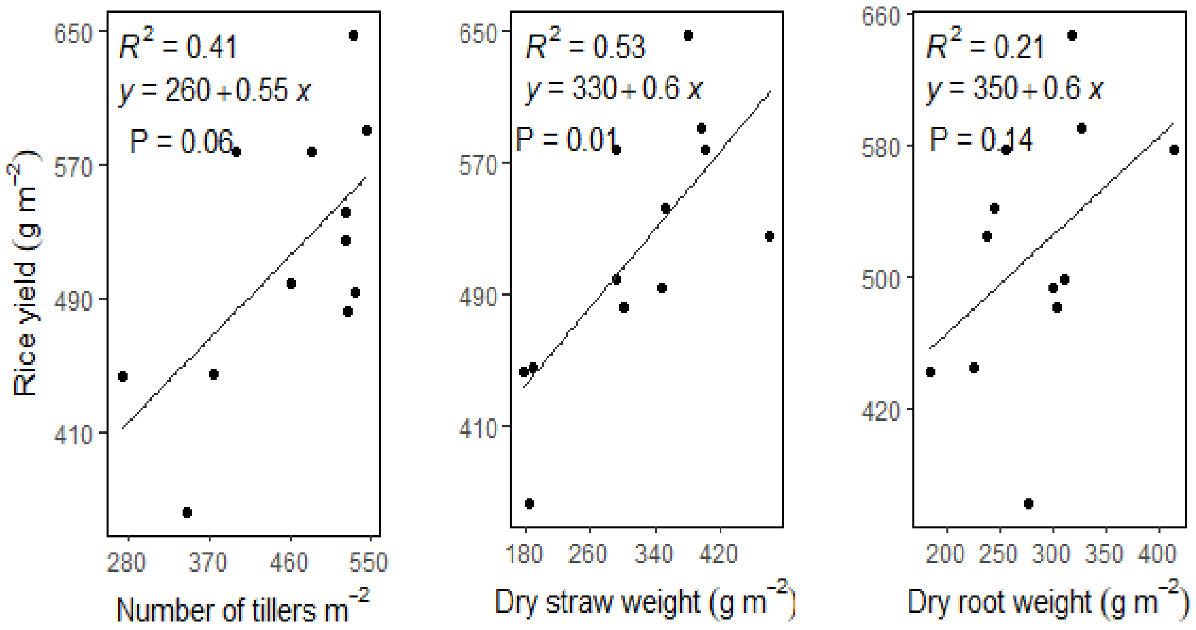


Figure 22: Relationship between rice yield and rice morphological traits at maturity stage under different treatments application during the 2021 and 2022 rice growing season.

4.3.8. Relationship between rice yield and GHGs emissions

Rice yield showed a weak and non-significant positive correlation with both temporal CH_4 and N_2O emissions (Figure 23). Since rice yield is a function of biological properties of plants such as rice tiller numbers, and total biomass, which are closely linked to GHGs emissions particularly CH_4, it is surprising that weak correlation was found for this study. No obvious explanation could be speculated for this apparent poor correlation coefficient aside, the contradictory role of different treatment effects on both GHGs and rice yield. While some treatments such as B2N2 promoted CH_4 and N_2O emission, its effect on yield was not as evident. On the other hand, B2N3 enhanced rice yield (Table 14) but was not very efficient in the promotion of GHGs emissions. These contradictory trends are speculated to be responsible for the observed poor relationship between rice yield and GHGs emissions.

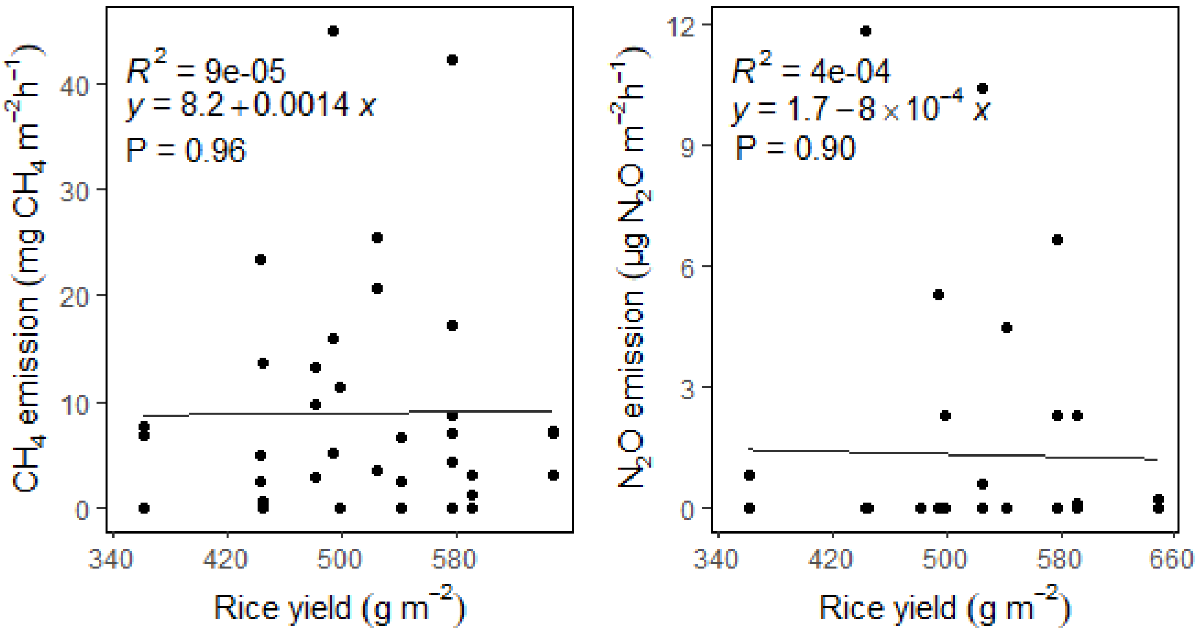


Figure 23: Relationship between rice yield and GHGs emissions under different treatments applications during the 2021 and 2022 rice growing seasons.

4.4. Residual effect of biochar and N-fertilization on soil physico-chemical properties after one season

After one season of rice growth, no significant effects of treatment applications were found on all the measured soil properties (Table 16). Variations were however observed under different treatments but these variations were insignificant at p<0.05. For instance, soil cation exchange capacity (CEC) varied from 0.03 cmol$^+$/kg (B2N3) to 0.04 cmol$^+$/kg (B1N1), while the lowest value (1.28 g/cm3) for bulk density (BD) was found B2N2 and highest value (1.61 g/cm3) in C1N2. Soil pH also varied from 5.74 (B2N3) to 5.93 (B1N3) while soil percentage organic carbon (Org_C) ranged from 2.54 % (B1N3) to 3.35 % (B2N2). For other macro-nutrients such as phosphorus (P), the mean values were between 3.76 mg/kg (C1N2) to 7.36 (B2N1) whereas for potassium (K) and magnesium (Mg), their mean values ranged from 1.83 mg/kg (B1N3) to 11.35 mg/kg (B1N1) and from 839 mg/kg in B1N3 to 973.67 recorded in B2N3 respectively. For the micro-nutrients, the mean values of iron (Fe) varied from 2742.33 mg/kg (B1N1) to 3423.67 mg/kg (BA) while the soil Zinc (Zn) content ranged from 7.67 mg/kg (B2N2) to 31.09 mg/kg (B2) and that of manganese (Mn) and cupper (Cu) varied from 156. 34 mg/kg (B1N1) to 244.52 mg/kg (B1N3) and 4.51 mg/kg (N3) to 27.18 mg/kg (B1N2) respectively.

The lack of significance observed across all the measured soil properties and treatments could be related to the low application rates of biochar in this study. Different researchers (Sandhu et al., 2017; Moragues-Saitua et al., 2017; Ghorbani et al., 2019) have attributed non-significant impact of biochar on soil properties to low application rates (<10 ton/ha). According to (Yao et al., 2017) the magnitude and potential of biochar to improve soil properties is dependent on biochar application rate. Despite many documented evidences of significant positive impact of biochar on soil properties (Jien and Wang, 2013; Thammasom et al., 2016; Tsai and Chang, 2019;Wacal et al., 2019), some researchers have documented non-significant (Sandhu et al., 2017; Moragues-Saitua et al., 2017; Ghorbani et al., 2019) and even negative effect of biochar on soil properties (Hailegnaw et al. 2019). The variation in biochar effect on soil properties were attributed to variation in soil properties (Jeffery et al., 2017).

Table 16: short term effect of biochar and N-fertiliser application on soil physico-chemical properties during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire.

Factors	BD (g/cm3)	CEC ($cmol^+/kg$)	pH	Org_C (%)	P (mg/kg)	K (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cu (mg/kg)
p-values	0.20	0.19	1.0	0.76	0.95	0.84	0.97	0.78	0.63	0.43	0.56
Trt											
B1	1.41a	0.03a	5.76a	2.90a	5.38a	8.63a	851.00a	2982.67a	17.77a	203.65a	6.72a
B2	1.46a	0.03a	5.85a	3.32a	6.23a	7.35a	965.33a	3414.00a	31.09a	214.32a	7.62a
BA	1.48a	0.03a	5.81a	2.67a	5.30a	9.52a	910.00a	3423.67a	7.91a	218.40a	6.43a
B1N1	1.52a	0.04a	5.77a	2.98a	7.04a	11.3a	905.00a	2742.33a	12.92a	156.34a	5.47a
B1N2	1.47a	0.03a	5.77a	3.26a	7.28a	8.92a	965.00a	3170.33a	12.76a	202.94a	27.18a
B1N3	1.41a	0.03a	5.93a	2.54a	4.45a	1.83a	839.00a	3247.00a	11.14a	244.52a	6.58a
B2N1	1.57a	0.03a	5.77a	3.0a	7.36a	7.16a	894.67a	3083.67a	14.54a	186.35a	11.90a
B2N2	1.28a	0.03a	5.89a	3.35a	7.20a	8.43a	944.33a	3048.00a	7.67a	201.07a	7.62a
B2N3	1.52a	0.02a	5.74a	3.27a	6.75a	8.51a	973.67a	3262.33a	10.01a	177.11a	7.11a
C1N2	1.61a	0.03a	5.92a	2.58a	3.76a	6.40a	906.67a	3278.67a	19.46a	217.68a	6.60a
N2	1.49a	0.03a	5.91a	3.31a	5.99a	7.05a	906.33a	3207.33a	18.09a	211.04a	4.51a
N3	1.51a	0.03a	5.78a	2.97	6.19a	8.67a	850.67a	2816.33a	9.61a	170.61a	12.10a

Trt: treatment, B1 (Biochar: 3t/ha), B1N1 (biochar: 3 t/ha + nitrogen: 60 kgN/ha), B1N2 (biochar: 3 t/ha+ nitrogen: 120 kgN/ha), B1N3 (biochar: 3 t/ha + nitrogen: 180 kgN/ha), B2 (biochar: 6 t/ha), B2N1(biochar: 6 t/ha+ nitrogen: 60 kgN/ha), B2N2 (biochar: 6 t/ha + nitrogen: 120 kgN/ha), B2N3 (biochar: 6 t/ha + nitrogen: 180 kgN/ha), BA (biochar: 3 t/ha + cow dung: 5 t/ha), C1N2 (hoe tillage + nitrogen: 120 kg/N/ha). Means with different letters under the same column are significantly different ($p<0.05$, TukeyHSD test)

CHAPTER FIVE

5.0. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

In the current study, effects of biochar and nitrogen fertiliser (N) on rice morphological traits, greenhouse gases emission, rice yield, harvest index and soil properties under combined application of biochar and N were evaluated. Our results indicated that the applications of either sole biochar or sole N were not effective in promoting rice morphological traits development. Whereas the application of biochar and N enhanced the growth of rice morphological traits compared to single application of biochar or N. Among the three traits evaluated (tillers, straw biomass and root biomass), straw biomass was most responsive to treatment applications. Combination of low biochar and high N rates (180 kgN/ha) was most efficient in increasing rice straw biomass which confirmed the hypothesis that co-application of biochar and N can enhance rice growth.

Sole biochar application especially at low rate, and low biochar rate with animal manure, significantly decreased cumulative nitrous oxide (N_2O) emissions, cumulative methane (CH_4) emissions, global warming potential (GWP) and greenhouse gas intensity (GHGI). Sole N application significantly enhanced GHGs emission, GWP, and GHGI more than sole biochar application. High N rates without biochar enhanced N_2O emission more than the control while co-application of biochar at 6 ton/ha with N at 120 kg N/ha significantly decreased CH_4 but increased N_2O emission GWP and GHGI relative to either sole N applied at the same rate with or without tillage application. Also combined application of biochar and N significantly enhanced carbon sequestration, rice yield especially at high biochar and medium or high N rates. Control treatment resulted in carbon loss from the soil and marginally increased rice yield and harvest index. Harvest index decreased under combined application of biochar and N but increased with sole biochar application.

This study confirmed our hypotheses that the co-application of biochar and N can reduce N_2O emissions at high biochar and low N rate but increase CH_4 emissions as well as rice yield at especially at high biochar and high N application rates.

For all the investigated growth stages, rice morphological traits weakly but positively correlated with GHGs emissions. Similar trends were also observed between rice morphological traits and rice yield but stronger relationships were observed between rice yield or GHGs emissions and rice straw than tiller numbers and root biomass. Moreso, weak and positive relationship was also found between rice yield and GHGs emissions.

Based on biochar application rates, arithmetic improvements in soil physicochemical properties were observed, however these improvements were not significantly different among treatments after one season of rice production.

In view of the high grain yield and carbon sequestration potential of B2N3 treatment, we conclude that B2N3 is the optimum biochar and N combination for maximizing rice yield and environmental protection.

5.2. Recommendation

Due to the low cost of rice husk used for biochar production and the high grain yield recorded when high N (180 kgN/ha) was combined with high biochar (6 ton/ha) (B2N3), we therefore recommend the use of B2N3 by local farmers in Cote D'Ivoire as it guarantees both rice yield and environmental protection. However, attention must be paid to the biochar production process as biochar produced from fast pyrolysis is associated with high content of polycyclic aromatic hydrocarbons (PAH); a by-product toxic to both plants and micro-organisms (Cayuela et al., 2014).

We also recommend that further researches be conducted in our African environment under different rice establishment method than direct seeding to test the evolution of greenhouse gases and rice yield under biochar and N fertiliser treatments

Considering that our study used a mixture of different N sources and the inadequacy of N fertiliser to farmers in Africa, studies investigating the role of biochar and different N sources on greenhouse gases and rice yield should be conducted. This is important as it will help to ascertain if the observed effects in this study is N source dependent.

Bearing in mind the challenges faced in our study and the urgent need to determine the accurate carbon footprint of agricultural systems in Africa, we recommend that governments and institutions in Africa should invest more resources in the purchase of equipment used for greenhouse gas studies such as gas chromatograph.

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ANNEXES

Appendix 1: ANOVA table for rice tillers numbers at tillering, heading and ripening during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire. TukeyHSD test ($p<0.05$)

		Tillering (tillers m^{-2})				Heading (tillers m^{-2})				Ripening (tillers m^{-2})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	5772	2886	0.38	0.69	19816	9908	2.35	0.12	2865	1433	0.55	0.58
Treatment (T)	11	74858	6805	0.9	0.56	267378	24307	5.75	0.00025	68213	6201	2.38	0.04
Error	22	166656	7575			92964	4226			57215	2601		
Total	35	247286	17266			380158	38441			128293	10235		
SD		84.06				104.22				60.54			
CV%		37.66				14.14				16.33			

Appendix 2: ANOVA table for rice tillers numbers at tillering, heading and ripening during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire. TukeyHSD test ($p<0.05$)

		Tillering (tillers m^{-2})				Heading (tillers m^{-2})				Ripening (tillers m^{-2})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	50296	25148	3.98	0.03	95223	47611	3.77	0.039	17089	8544	2.5	0.1
Treatment (T)	11	148241	13476	2.14	0.06	323593	29418	2.33	0.04	178400	16218	4.75	9.30E-04
Error	22	138872	6312			278017	12637			75145	3416		
Total	35	337409	44936			696833	89666			270634	28178		
SD		98.18				141.10				87.93			
CV%		30.14				26.45				15.70			

Appendix 3: ANOVA table for rice straw at tillering, heading and ripening during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 at the AfricaRice research field M‘be, Bouaké, Côte d’Ivoire. TukeyHSD test ($p<0.05$)

		Tillering (g m^{-2})				Heading (g m^{-2})				Ripening (g m^{-2})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	0.0036	0.0018	0.14	0.87	9906	4953	1.24	0.31	50328	25164	0.87	0.43
Treatment (T)	11	0.2	0.018	1.41	0.24	303146	27559	6.9	6.51E-05	481554	43778	1.51	0.2
Error	22	0.28	0.013			87855	3993			636834	28947		
Total	35	0.48	0.033			400907	36505			1168716	97889		
SD		0.12				107.03				182.73			
CV%		36.94				19.95				30.53			

Appendix 4: ANOVA table for rice straw at tillering, heading and ripening during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire. TukeyHSD test ($p<0.05$)

	Tillering (g m^{-2})					Heading (g m^{-2})				Ripening (g m^{-2})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	13.35	6.68	6.1	0.0078	15252	7626	1.94	0.17	5276	2638	0.12	0.89
Treatment (T)	11	10.55	0.96	0.88	0.58	218066.00	19824	5.05	0.00062	1142450	103859	4.544	0.0012
Error	22	24.09	1.1			86312	3923			502796	22854		
Total	35	47.99	8.74			319630	31373			1650522	129351		
SD		1.17				95.56				217.16			
CV%		33.56				16.96				17.16			

Appendix 5: ANOVA table for rice dry root at tillering, heading and ripening during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2021 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire. TukeyHSD test ($p<0.05$)

		Tillering (g m^{-2})				Heading (g m^{-2})				Ripening (g m^{-2})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	0.67	0.05	0.78	0.47	37032	18516	1.4	0.27	112113	56057	2.63	0.09
Treatment (T)	11	0.09	0.06	1.04	0.45	118588	10781	0.81	0.63	131341	11940	0.56	0.84
Error	22	1.28	0.06			291193	13236			468759	21307		
Total	35	2.04	0.17			446813	42533			712213	89304		
SD		0.2				112.99				142.65			
CV%		47.85				40.65				39.99			

Appendix 6: ANOVA table for rice dry root at tillering, heading and ripening during the study of biochar and N-fertilization effects on greenhouse gases emissions and productivity of lowland rice under zero tillage conducted in 2022 at the AfricaRice research field M'be, Bouaké, Côte d'Ivoire. TukeyHSD test ($p<0.05$)

		Tillering (g m^{-2})				Heading (g m^{-2})				Ripening (g m^{-2})			
Sources of variation	Df	SS	MS	F	P	SS	MS	F	P	SS	MS	F	P
Rep	2	2.68	1.34	1.26	0.30	6358	3179	0.42	0.66	288855	144428	15.09	7.48e-05
Treatment (T)	11	25.04	2.28	1.13	0.06	90017	8183	1.09	0.41	170024	15457	1.62	0.16
Error	22	23.48	1.07			165278	7513			210548	9570		
Total	35	51.2	4.69			261653	18875			669427	169455		
SD		1.21				86.46				138.30			
CV%		47.85				42.31				38.27			