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Enhancing rice productivity and mitigating greenhouse gas emissions through manure maturity and water management in paddy soils

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ABSTRACT

This study investigates the influence of manure maturity and water management practices on greenhouse gas (GHG) emissions and rice yield in paddy soils. Field experiments were conducted with different manure types (raw and mature) under two water management conditions: flooded and non-flooded. The emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were measured throughout the growing season, alongside rice yield, global warming potential (GWP), and greenhouse gas intensity (GHGI). The results revealed that mature manure (B2) under flooded conditions (G2) significantly reduced CO_2 and CH_4 emissions while enhancing rice yield (5.87 tons/ha) compared to raw manure treatments. The B2G2 treatment demonstrated the lowest GWP (153.49 kg CO_2e/ha) and GHGI (26.16 kg CO_2e/kg grain yield), indicating optimal environmental efficiency. In contrast, the B1G1 treatment (raw manure under non-flooded conditions) resulted in the highest GHG emissions and the lowest rice yield (3.57 tons/ha). This study highlights the potential of integrating mature organic amendments with controlled water management to reduce the environmental impact of rice cultivation while maintaining high productivity, offering a sustainable approach to rice farming in the face of climate change challenges.

Keywords: global warming potential, greenhouse gas, rice, sustainability.

INTRODUCTION

Rice is a staple crop with high levels of production and consumption (Li et al., 2021). The growing demand for rice has driven intensive exploitation of paddy fields to increase production (Bin Rahman & Zhang, 2023). However, excessive land management can negatively impact the environment, such as water wastage and overuse of fertilizers. One consequence of such management is the increase in greenhouse gas (GHG) emissions, including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). These emissions are influenced by water management and the type of organic materials used. Indonesia, as one of the major rice producers in Asia, significantly contributes to methane emissions from paddy fields (Zhang et al., 2016). It is estimated that approximately 80% of global methane emissions originate from water-saturated lands, such as paddy fields and peat swamps (Yang et al., 2009).

Anaerobic conditions in water-saturated soils of paddy fields are the primary trigger for methane production, while variations in water saturation affect nitrous oxide emissions (Wüst-Galley et al., 2023). The use of organic manure also influences GHG emissions through microbiological processes such as denitrification and methane production. The maturity of manure is a crucial factor affecting the level of these emissions (Liu et al., 2024). A thorough understanding of the relationship between water management and manure maturity is key to minimizing the negative environmental impacts of rice farming, especially on sandy loam soils with unique water retention characteristics (Han et al., 2024).

The type and maturity of manure significantly contribute to GHG emissions from paddy fields. Fresh or partially decomposed manure tends to generate higher methane emissions than fully composted manure due to differences in organic matter decomposition levels (Takakai et al., 2017). Additionally, increased water saturation in soil elevates methane and nitrous oxide emissions, as these conditions shift microbial activity toward denitrification (Zhu et al., 2014; Lakshani et al., 2023). Thus, efforts to understand and manage these relationships form the foundation for developing sustainable farming practices that maintain rice productivity while reducing GHG emissions.

Various studies have focused on reducing GHG emissions in paddy fields through water management and more effective use of organic fertilizers. Practices such as alternate wetting and drying (AWD) irrigation have been proven to reduce methane emissions by limiting the duration of anaerobic conditions (Dahlgreen & Parr, 2024). Moreover, using mature organic manure can improve soil nutrient balance while suppressing the potential for methane and nitrous oxide emissions (Zhu et al., 2014). These strategies highlight the potential for integrating precise water management with organic amendments to support sustainable rice cultivation in sandy loam soils.

The interaction between water saturation levels and manure maturity is of particular concern for soils with low water retention, such as sandy loam. On such soils, proper water management can significantly reduce methane emissions, enhance nutrient availability, and suppress N2O emissions (Hassan et al., 2022). Therefore, soil- and region-specific management approaches are essential to maximize the effectiveness of these practices (Huang & Hartemink, 2020).

The complex interplay between water management, manure maturity, and GHG emissions from paddy fields is a critical factor in mitigating climate change impacts. Combining mature organic manure with precise water management offers a promising solution for achieving sustainable rice farming, especially in sandy loam soils. This study will test water management and manure maturity in controlled conditions to assess GHG emissions, providing a basis for strategies that can be widely applied in rice-producing regions with similar land characteristics.

MATERIAL AND METHOD

Site description

This study was conducted from June to August 2024 at the experimental farm of the Stiper Agricultural University, Yogyakarta. The research site is located on alluvial plains with geographical coordinates of 7°55’57.82”S and 110°22’16.91”E. The soil used as the planting medium was collected from paddy fields at a depth of 0–30 cm, representing the plow layer (Ap horizon). The soil has a sandy loam texture with a pH of 6.3. Climatic data during the study were obtained from the climatology station of the Stiper Agricultural Institute using an ATMOS 41 sensor. The recorded climate parameters included solar radiation, air temperature, humidity, and rainfall. During the three-month study period, no rainfall occurred because the research took place during the dry season, which extends from April to October 2024. The average solar radiation was recorded at 410.51 W/m², with an average air temperature of 28.02°C and an average humidity of 29.96%. These climate parameters were considered as they could influence greenhouse gas emissions during the study. Figure 1 shows the climatic characteristics during the study.

Experimental design

This study was designed using a Randomised Complete Block Design (RCBD) with six treatment combinations, each replicated three times, resulting in a total of 18 experimental plots. The treatment factors consisted of the type of organic fertilizer and water conditions. The types of organic fertilizer included: no cow manure-based organic fertilizer (B0), raw cow manure-based organic fertilizer (B1), and mature cow manure-based organic fertilizer (B2). The water conditions were categorized as non-flooded soil (G1) and flooded soil with a water depth of 5 cm (G2).

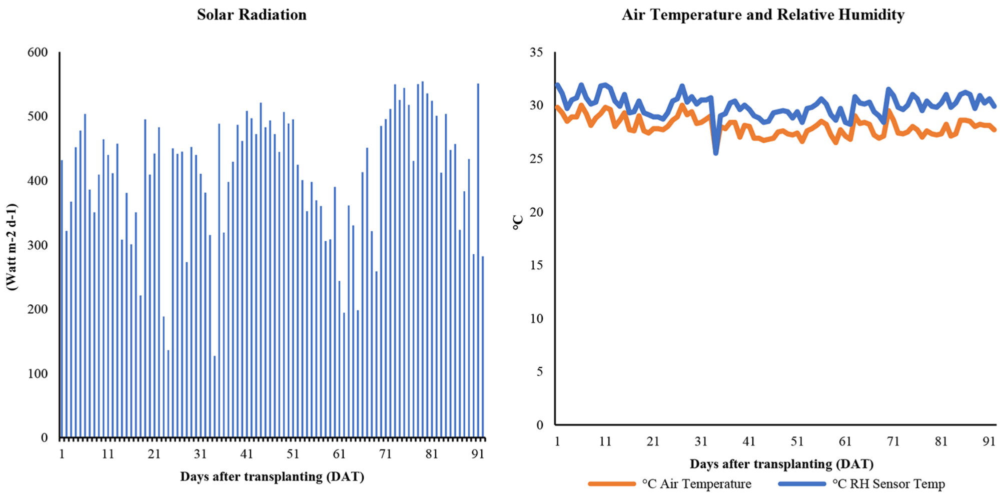

Figure 1. The climatic characteristics

The rice variety used in this study was Inpari 42. Seeds were germinated for three weeks before being transplanted into experimental buckets, with each bucket containing three rice plants. As a basal fertilizer, 100 kg/ha NPK was applied at 7 days after transplanting (DAT). Supplemental fertilization was applied at 21 DAT using 100 kg/ha of NPK and 100 kg/ha of SP36, followed by a second application at 35 DAT using 100 kg/ha of NPK and 100 kg/ha of KCl. The dosage of both raw and mature cow manure-based organic fertilizers was calculated based on soil volume and bulk density, equivalent to 20 tons/ha.

Throughout the study, various management activities were carried out to maintain the continuity of the experiment, including pest control, water condition adjustments according to treatments, and monitoring the vegetative growth of the plants. Soil saturation levels were controlled through irrigation or flooding, aligned with the treatment combinations, to ensure the accuracy of the results obtained from each experimental plot.

The weekly observations conducted during the study also measured soil chemical properties that influence greenhouse gas emissions. The soil properties measured include electrical conductivity, soil pH, and redox potential. These properties are key factors in determining the dynamics of greenhouse gas emissions produced by rice plants.

Gas sampling and analysis

Gas sampling for the analysis of CO_2, CH_4, and N_2O emissions was conducted using the static closed chamber-GC method (Nie et al., 2023) every seven days after rice was planted. The sampling chamber was a cylindrical tube with a diameter of 30 cm and a height of 150 cm, made of transparent acrylic. The chamber's diameter matched the experimental bucket's diameter to create an airtight space without leakage. Each chamber was equipped with a battery-powered fan to ensure air homogeneity and a thermometer to record the internal temperature for gas emission rate calculations. Gas samples were collected using an airtight 10 mL syringe attached to the chamber wall through a three-way stopcock. Sampling was performed weekly between 09:00 and 11:00 AM, with four gas samples taken at 10-minute intervals (0, 10, 20, and 30 minutes) during each session. The gas samples were then transferred to 10 mL vacuum glass vials sealed with butyl rubber septa for laboratory analysis.

CH_4 and N_2O concentrations were analyzed using gas chromatography (Shimadzu GC-2014, Japan), equipped with a flame ionization detector (FID) for CH_4 and an electron capture detector (ECD) for N_2O. The column was packed with ProPak Q (80–100 mesh) and maintained at a temperature of 50 °C. The detector temperatures were set to 150 °C for FID and 300 °C for ECD. Nitrogen (N_2) was used as the carrier gas for CH_4 analysis, while argon was used for N_2O analysis. Hydrogen and air were utilized as combustion and supporting gases for CH_4 analysis. Gas samples were analyzed within one week of collection.

Greenhouse gases emission calculation

The emission fluxes (*f*) were calculated from the slope of the linear regression between the concentration of CO_2, CH_4 or N_2O and the chamber closure time. This slope value was then converted into the mass of gas per unit area and time (mg m^{-2} d^{-1}) using the following formula (Han et al., 2024; Xu et al., 2023; Islam et al., 2020):

$$f = \frac{Slope\,(\text{ppm min}^{-1}) \times Vc \times MW \times 60 \times 24}{22.4 \times \left(273 + \frac{T}{273}\right) \times Ac \times 1000} \quad (1)$$

where: f – the CO_2, CH_4 or N_2O emission fluxes (mg m^{-2} d^{-1}), Vc – represents the volume of the gas chamber in liters (L), MW – the molecular weight of the respective gas, 60 – corresponds to minutes per hour (min h^{-1}), 24 – represents hours per day (h d^{-1}), 22.4 – the volume of 1 mole of gas in liters (L) at standard temperature and pressure, 273 – the standard temperature in Kelvin (°K), T – the temperature inside the chamber in Celsius (°C), Ac – the area of the chamber in square meters (m^2), and 1000 – the conversion factor from micrograms (µg) to milligrams (mg^{-1}).

The cumulative emissions of CH_4 and CO_2 were calculated as follows:

$$F = \sum_{i=1}^{n} \left(\frac{f_i + f_{i+1}}{2}\right) \times (t_{i+1} - t_i) \times 24 \quad (2)$$

where: F – the seasonal emissions of each gas (kg ha^{-1}); f_i and f_{i+1} – two adjacent gas emission fluxes (kg ha^{-1} h^{-1}); t_i and t_{i+1} – are two adjacent sampling times; 24 – the conversion coefficient between hours and days.

Global warming potential (GWP) is calculated using the formula:

$$GWP\ (\text{kg } CO_2 equivalent\ ha^{-1}) = (TCO_2 \times 1 + TCH_4 \times 28 + TN_2O \times 265) \quad (3)$$

where: TCO_2 – refers to the total amount of CO_2 emissions (kg ha^{-1}), TCH_4 – the total amount of CH_4 emissions (kg ha^{-1}), TN_2O – the total amount of N_2O emissions (kg ha^{-1}). The GWP values for each gas are based on the IPCC 2014 guidelines (Pachauri et al., 2015).

The greenhouse gas emission intensity is calculated using the following equation:

$$GHGI = \frac{GWP}{Yield} \quad (4)$$

where: $GHGI$ – represents the total greenhouse gas emissions per unit of rice yield (kg CO_2 equivalent per kg of grain yield).

RESULT

Dynamics of CO_2- CH_4- N_2O emissions

The emission rates of CO_2 exhibited significant variation throughout the growing period, peaking around 30 days after transplanting (DAT) across all treatments. At this point, the highest emission was observed in the treatment with raw manure under flooded conditions (B1G2), reaching approximately 750 mg m^{-2} day^{-1}, while the lowest emissions were recorded in the mature manure non-flooded treatment (B2G1), around 500 mg m^{-2} day^{-1} (Fig. 2a). These elevated emissions during the early stages of growth correlate with heightened root respiration and microbial activity.

Flooded soil treatments (G2) generally produced higher CO_2 emissions than non-flooded treatments (G1), with averages of around 600–700 mg m^{-2} day^{-1} in G2 compared to 500–600 mg m^{-2} day^{-1} in G1. Emissions gradually decreased after the reproductive stage, falling to approximately 300–400 mg m^{-2} day^{-1} by 70–90 DAT (Fig. 2a). Notably, the B2 treatments (mature manure) consistently demonstrated lower CO_2 emissions compared to B0 (no manure) and B1 (raw manure), underscoring the role of manure maturity in reducing labile carbon availability and microbial respiration rates.

CH_4 emissions were heavily influenced by water management, with flooded conditions (G2) showing significantly higher emissions than non-flooded conditions (G1). The peak emissions occurred around 20–30 DAT, with the B0G2 treatment (no manure under flooded conditions) reaching approximately 2.5 mg m^{-2} day^{-1}. In contrast, the lowest emissions were observed in the B2G1 treatment (mature manure under non-flooded conditions), at around 0.5 mg m^{-2} day^{-1} (Fig. 2b).

The application of raw manure (B1) under flooded conditions (B1G2) resulted in the highest overall CH_4 emissions during the study, averaging between 1.5–2.5 mg m^{-2} day^{-1}. Mature manure (B2) significantly reduced methane emissions, with values ranging from 0.5–1.0 mg m^{-2} day^{-1} under flooded conditions and less than 0.5 mg m^{-2} day^{-1} under non-flooded conditions. This reduction is attributed to the lower availability of decomposable organic matter in mature manure. By 70–90 DAT, CH_4 emissions declined substantially, stabilizing below 0.5 mg m^{-2} day^{-1} across all treatments (Fig. 2b).

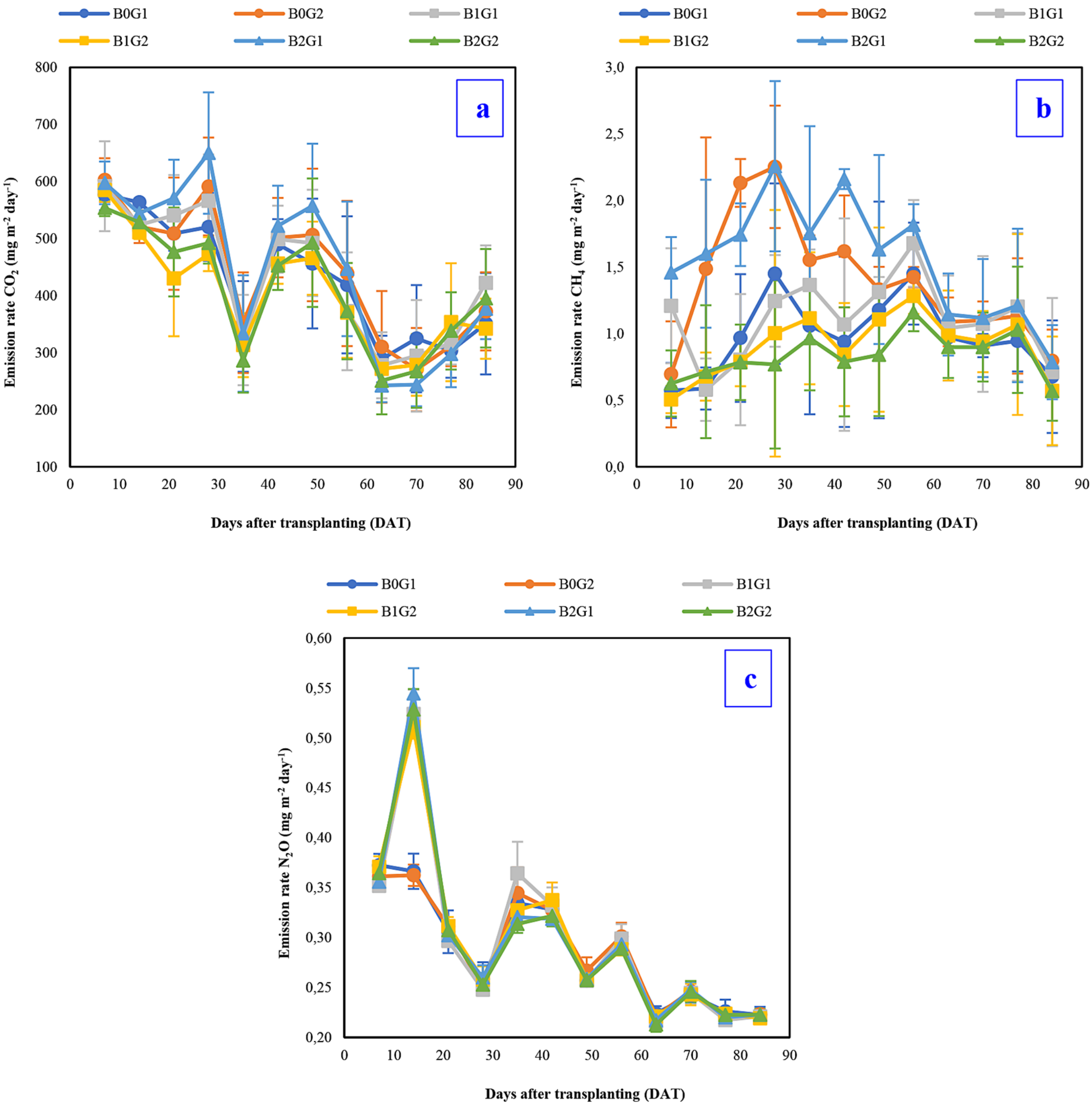

Figure 2. Dynamic of greenhouse gas emission (a) CO_2; (b) CH_4; (c) N_2O

N_2O emissions showed a sharp peak between 10–20 DAT, with the highest emission rate observed in the B1G1 treatment (raw manure under non-flooded conditions) at approximately 0.55 mg m^{-2} day^{-1}. In comparison, the lowest N_2O emissions were recorded in the B2G2 treatment (mature manure under flooded conditions), averaging 0.20–0.25 mg m^{-2} day^{-1} during this period (Fig. 2c).

Non-flooded treatments (G1) consistently generated higher N_2O emissions than flooded treatments (G2). For example, emissions in G1 ranged from 0.30–0.55 mg m^{-2} day^{-1} during the early growth stages, while G2 emissions remained below 0.30 mg m^{-2} day^{-1}. As the season progressed, N_2O emissions declined across all treatments, stabilizing around 0.20 mg m^{-2} day^{-1} by 70–90 DAT (Fig. 2c). The application of mature manure (B2) significantly mitigated N_2O emissions, demonstrating the importance of stable nitrogen release in reducing nitrogen losses and environmental impacts.

Cumulative emission

From the CO_2 data, we can observe that the highest emissions occur under the treatment B1G1 (150.57 kg ha^{-1} h^{-1}), suggesting that this particular combination of factors leads to higher CO_2 release compared to the other treatments. Conversely, the lowest CO_2 emission is recorded under B1G2 (111.87 kg ha^{-1} h^{-1}), which is almost 39 kg ha^{-1} h^{-1}

lower than B1G1 (Fig. 3a). This variance indicates that the factors present in these treatments, such as soil composition or agricultural inputs, might significantly influence the rate of CO_2 release, possibly due to differences in microbial activity, organic matter decomposition, or soil aeration.

Regarding CH_4 emissions (Fig. 3b), the highest levels are recorded under the treatment B2G1 (1.38 kg ha^{-1} h^{-1}), while the lowest methane emissions are found under B2G2 (0.66 kg ha^{-1} h^{-1}). These differences could be attributed to variations in factors like soil moisture, temperature, and organic matter content, which can affect methanogenic microorganisms in the soil. Methane is often produced in anaerobic conditions, such as in flooded rice paddies, so the treatments with higher methane emissions may indicate a higher level of water saturation or organic content conducive to methanogenesis. For N_2O, the emissions appear to be relatively stable across all treatments, ranging from 0.0799 to 0.0838 kg ha^{-1} h^{-1} (Fig. 3c). Although the variations are smaller compared to CO_2 and CH_4 emissions, the consistency in N_2O emissions suggests that the treatments do not significantly influence N_2O production. N_2O is typically produced during nitrification and denitrification processes in the soil, often in the presence of excess nitrogen. This uniformity in the N_2O data may indicate that nitrogen availability, which may not differ greatly among the treatments, is a more significant driver of emissions than other factors. The data suggests that different agricultural treatments can have varying impacts on greenhouse gas emissions, with CO_2 and CH_4 showing more pronounced differences across treatments than N_2O. Understanding the specific factors that lead to higher emissions of these gases could help in designing more sustainable agricultural practices

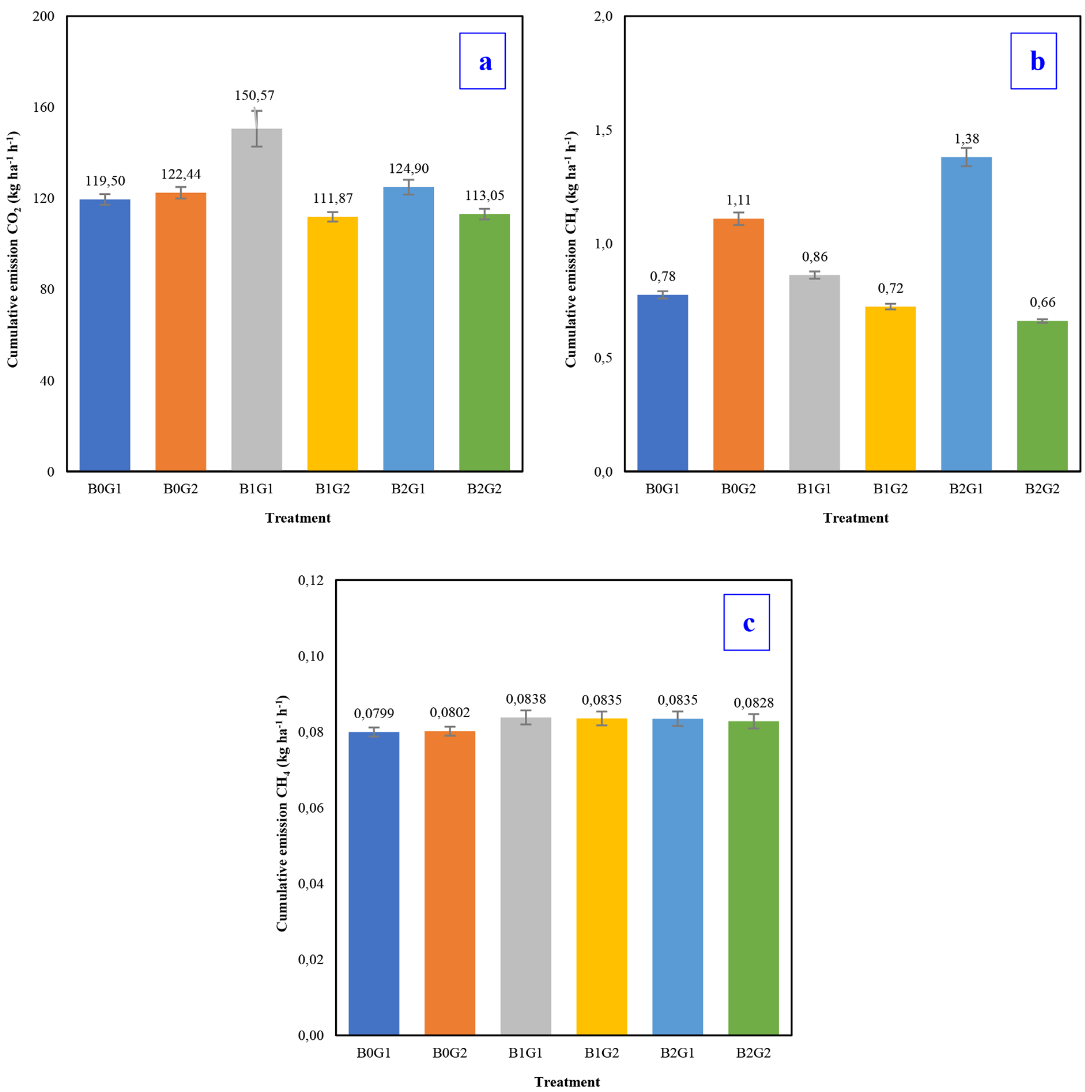

Figure 3. Cummulative emission of greenhouse gas (a) CO_2; (b) CH_4; (c) N_2O

that minimize greenhouse gas release, contributing to better environmental outcomes.

GWP, rice yield, and GHGI

The GWP is expressed in kilograms of CO_2 equivalent per hectare (kg CO_2e ha^{-1}), representing the overall impact of the treatment on global warming. When examining the GWP, the highest value is observed for the treatment B1G1, which has a GWP of 196.93 kg CO_2e ha^{-1} (Fig. 4a). This treatment also shows the lowest grain yield of 3.57 tons per hectare (Fig. 4b), suggesting that the combination of factors in this treatment may result in greater emissions and lower productivity. On the other hand, treatment B2G2, with a GWP of 153.49 kg CO_2e ha^{-1} (Fig. 4a), exhibits the second-lowest environmental impact in terms of global warming potential. Interestingly, this treatment also achieves the highest grain yield (5.87 tons per hectare), indicating that it not only has lower emissions but also excels in terms of productivity, making it a more sustainable option. The variation in global warming potential and grain yield between treatments indicates that higher emissions do not necessarily correlate with higher productivity. For example, treatment B0G1, with a GWP of 162.41 kg CO_2e ha^{-1} (Fig. 4a), has a grain yield of 5.21 tons per hectare (Fig. 4b), which is relatively high compared to B1G1 but with a significantly lower GWP. This highlights that certain treatments may offer a better balance between greenhouse gas emissions and grain yield.

In terms of greenhouse gas intensity, which measures the environmental efficiency of each treatment, treatment B2G2 emerges as the most efficient with an intensity of 26.16 kg CO_2e kg^{-1} grain yield (Fig. 4c). This means that B2G2 produces

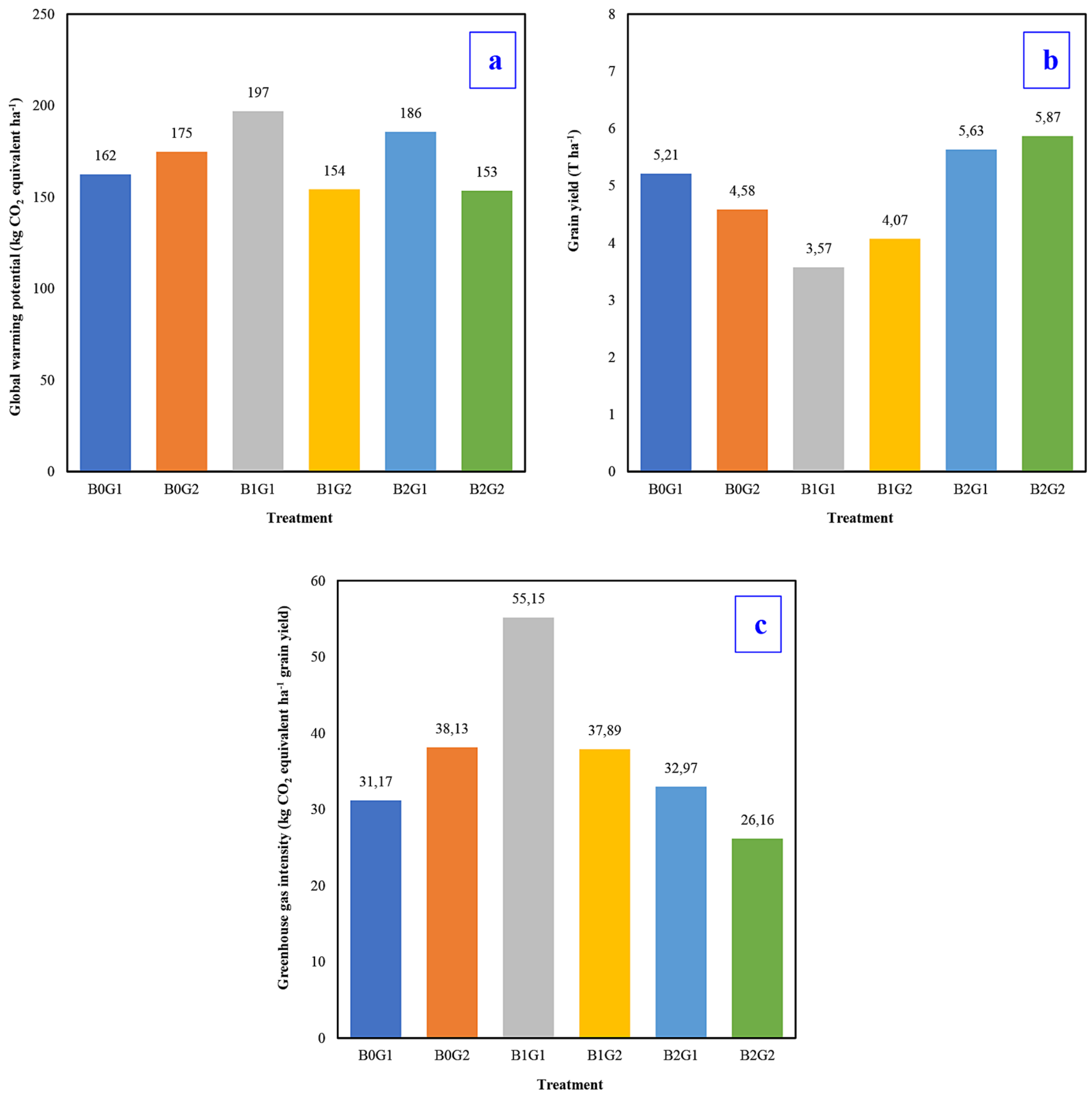

Figure 4. Effect of water and manure management on (a) GWP; (b) rice yield; (c) GHGI

the least greenhouse gas emissions per kilogram of grain harvested. In contrast, treatment B1G1 has the highest greenhouse gas intensity (55.15 kg CO_2e kg^{-1} grain yield) (Fig. 4c), reflecting both its higher emissions and lower productivity.

DISCUSSIONS

The interaction between manure maturity and water management significantly affects greenhouse gas (GHG) emissions from paddy soils, as evidenced by the observed dynamics of CO_2, CH_4, and N_2O emissions. The results demonstrate that the emission rates of these gases vary markedly with manure maturity and water conditions, aligning with established findings on gas exchange mechanisms in flooded and non-flooded paddy systems. Mature manure (B2) generally resulted in lower emissions of CO_2 and CH_4 compared to raw manure (B1), while water management strategies further modulated these emissions.

CO_2 emissions were predominantly driven by microbial respiration and the decomposition of organic matter. The highest CO_2 emissions were observed in the B1G1 treatment, where raw manure was applied under non-flooded conditions, peaking at approximately 150.57 kg CO_2 ha^{-1} (Fig. 3a). This result aligns with previous studies indicating that raw manure provides a readily available carbon source for microbial decomposition, enhancing CO_2 release under aerobic conditions (Smith et al., 2020). In contrast, treatments with mature manure (B2) showed consistently lower CO_2 emissions, with cumulative emissions around 111.87 kg CO_2 ha^{-1} (Fig. 3a), likely due to the reduced availability of labile carbon in mature manure. Additionally, flooded conditions (G2) generally resulted in lower CO_2 emissions compared to non-flooded conditions (G1), as anaerobic environments limit the activity of aerobic microbes responsible for CO_2 production.

CH_4 emissions were heavily influenced by water management, with flooded treatments (G2) exhibiting significantly higher CH_4 emissions than non-flooded treatments (G1). Peak CH_4 emissions in the B1G2 treatment (raw manure under flooded conditions) reached approximately 2.5 mg CH_4 m^{-2} day^{-1} (Fig. 2b), with cumulative emissions averaging 1.38 kg CH_4 ha^{-1} (Fig. 3b). This finding is consistent with the role of anaerobic conditions in promoting methanogenesis, a process facilitated by methanogenic archaea in water-saturated soils (Le Mer & Roger, 2001). In contrast, mature manure (B2) significantly reduced CH_4 emissions, with cumulative emissions as low as 0.66 kg CH_4 ha^{-1} (Fig. 3b), likely due to the lower availability of easily decomposable organic matter, corroborating findings by (Shakoor et al., 2021). N_2O emissions, on the other hand, were primarily influenced by soil nitrogen availability and aeration. Non-flooded treatments (G1) showed higher N_2O emissions than flooded treatments (G2), as aerobic conditions favor nitrification and denitrification processes that produce N_2O (Butterbach-Bahl et al., 2013). The highest N_2O emissions were observed in the B1G1 treatment, where raw manure under non-flooded conditions provided an abundant nitrogen source for microbial processes, peaking at approximately 0.55 mg N_2O m^{-2} day^{-1} (Fig. 2c). Conversely, mature manure (B2) reduced N_2O emissions across all water conditions, with cumulative emissions as low as 0.20–0.25 mg N_2O m^{-2} day^{-1} (Fig. 2c), likely due to its more stable nitrogen release patterns, reducing the availability of excess nitrogen for nitrification and denitrification.

Cumulative GHG emissions highlight the combined impact of water and manure management on overall emissions. Treatments with intermittent flooding (G1) generally resulted in higher cumulative CO_2 (150.57 kg ha^{-1}) and N_2O emissions (0.0838 kg ha^{-1}) but lower CH_4 emissions (0.66 kg ha^{-1}) compared to continuous flooding (G2) (Fig. 3c). These findings align with research by Gao et al. (2024), which demonstrated that alternating aerobic and anaerobic conditions can enhance CO_2 and N_2O emissions while mitigating CH_4 emissions. The B2G2 treatment (mature manure under flooded conditions) emerged as the most environmentally favorable option, with lower cumulative emissions across all three gases.

Rice yield data further underscore the interplay between productivity and environmental impact. The highest grain yield of 5.87 tons per hectare was observed in the B2G2 treatment (Fig. 4b), suggesting that mature manure under flooded conditions provides optimal nutrient availability without excessively increasing GHG emissions. This result aligns with studies emphasizing the role of organic amendments in enhancing soil fertility and crop productivity (Wang et al., 2020). In contrast, treatments with raw manure (B1) generally showed lower yields (3.57 tons per hectare) and higher emissions (Fig. 4b), reflecting inefficiencies in nutrient utilization and greater environmental impacts. Global Warming Potential (GWP) and

Greenhouse Gas Intensity (GHGI) metrics provide a comprehensive assessment of the environmental efficiency of each treatment. The B2G2 treatment exhibited the lowest GWP (153.49 kg CO_2e ha^{-1}) (Fig. 4a) and GHGI (26.16 kg CO_2e kg^{-1} grain yield) (Fig. 4c), indicating that it achieves the best balance between reducing emissions and maximizing yield. This aligns with the findings of (Lakshani et al., 2023), who demonstrated that optimized water and manure management can significantly reduce the climate impact of rice production. Conversely, the B1G1 treatment had the highest GWP (196.93 kg CO_2e ha^{-1}) (Fig. 4a) and GHGI (55.15 kg CO_2e kg^{-1} grain yield) (Fig. 4c), highlighting the environmental costs of raw manure application under non-flooded conditions.

The observed variations in GWP and GHGI underscore the importance of integrating water and manure management strategies to achieve sustainable rice production. Flooded conditions with mature manure (B2G2) not only minimized GHG emissions but also supported higher yields, demonstrating the potential of such practices to enhance both environmental and agricultural outcomes. These findings support the broader application of mature organic amendments and controlled water management as key components of sustainable rice farming systems.

CONCLUSIONS

This study highlights the pivotal role of manure maturity and water management in regulating greenhouse gas (GHG) emissions and optimizing rice productivity in paddy soils. The application of mature manure under flooded conditions (B2G2) emerged as the most effective practice, achieving the highest rice yield of 5.87 tons per hectare while significantly reducing cumulative emissions of CO_2, CH_4, and N_2O. Specifically, this treatment demonstrated the lowest global warming potential (153.49 kg CO_2e ha^{-1}) and greenhouse gas intensity (26.16 kg CO_2e kg^{-1} grain yield), indicating an optimal balance between environmental sustainability and agricultural output. In contrast, raw manure application under non-flooded conditions (B1G1) resulted in the highest GHG emissions and lowest yield, underscoring the inefficiencies and environmental drawbacks of this approach. These findings underscore the importance of integrating mature organic amendments with controlled water management to mitigate climate impacts while ensuring high crop productivity, providing a sustainable pathway for rice cultivation in the context of global environmental challenges.

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