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Assessment of the impact of fertilizers on greenhouse gas emissions in Rambutan growing soil

Binh Van Vo[1], Canh Linh Mai[1], Linh Ba Tran[2], Dung Van Tran[2], Minh Quang Vo[3*]

[1] Applied Biology Faculty, Tay Do University, Tran Chien Street, Cantho City, Vietnam
[2] Faculty of Soil Science, College of Agriculture, Can Tho University, Can Tho City, 90000, Vietnam
[3] College of Environment and Natural Resources, Can Tho University, Can Tho City, 90000, Vietnam
* Corresponding author's email: vqminh@ctu.edu.vn

ABSTRACT

The subsequent evaluation of our study involved a field experiment conducted on a 17-year-old rambutan orchard soil in Phu Phung commune, Cho Lach district, Ben Tre province. The experiment evaluated the effects of three types of organic fertilizers – sugarcane compost, biogas residue, and vermicompost – which were applied at 18 kg per tree. To compare these treatments to a control treatment based on local farmers' practices, which used solely inorganic fertilizers (2.2 kg N, 1.5 kg P_2O_5, and 0.3 kg K_2O per tree), they were coupled with the required inorganic fertilizers (1.5 kg N, 1.0 kg P_2O_5, and 1.7 kg K_2O per tree). The findings demonstrated a considerable rise in CO_2 emissions from all organic fertilizer treatments but significantly reduced N_2O emissions ($p < 0.05$) compared to the farmers' practice. The global warming potential (GWP) of the farmers' practice ranged from 0.51 to 6.66 $g \cdot m^{-2} \cdot h^{-1}$ CO_2-equivalent, while the sugarcane compost treatment exhibited the lowest GWP, ranging from 0.22 to 4.02 $g \cdot m^{-2} \cdot h^{-1}$ CO_2-equivalent ($p < 0.05$). CO_2 emissions were strongly correlated with soil organic matter, soil temperature, and air temperature, with R^2 values of 0.82, 0.81, and 0.81, respectively. At the same time, N_2O emissions were closely linked to soil moisture, the water level in irrigation ditches, and the total amount of NH_4^+ and NO_3^-, with R^2 values of 0.85, 0.82, and 0.68, respectively. This study offers important new information about how organic fertilizers might reduce greenhouse gas emissions from Vietnam's rambutan production, contributing to more sustainable fruit production and climate change adaptation.

Keywords: carbon dioxide, climate change, fertilizer, nitrous oxide, organic matter, rambutan.

INTRODUCTION

Ben Tre Province, Vietnam, has a rambutan cultivation area of approximately 3.692 hectares, producing 73,607 tons annually, accounting for 70% of the total Rambutan growing area in the Mekong Delta (MD). According to the Statistical Yearbook (2023), Cho Lach District contributes 2.383 hectares and an output of 47,369 tons. Rambutan (*Nephelium lappaceum* L.) is a high-value fruit crop with substantial nutritional and economic benefits for local farmers. However, long-term cultivation practices that rely heavily on inorganic fertilizers may lead to reduced productivity and increased greenhouse gas (GHG) emissions. Globally, agriculture contributes approximately 10–14% of anthropogenic GHG emissions, primarily from fertilizer application and livestock production (Shakoor et al., 2021). Atmospheric CO_2 concentrations have continued to rise, exceeding pre-industrial period levels by nearly 100 ppm (Shibata et al., 2016). Field crops, such as legumes, oilseeds, vegetables, and fruit trees, produce considerable greenhouse gas emissions (Chaut et al., 2023). Methane (CH_4) from the anaerobic breakdown of organic matter, nitrous oxide (N_2O) from nitrification and denitrification processes, and CO_2 emissions from fertilizer use are the primary agricultural sources of greenhouse gases (Zaman et al., 2021; Venterea et al., 2005). Nitrogen-based fertilizers, especially urea, play a significant role in N_2O emissions by supplying substrates for microbial transformations (Groenigen, 2010). The urease enzyme hydrolyzes urea

($CO(NH_2)_2$) when it is added to soil, producing ammonium (NH_4^+), hydroxide ions (OH^-), and bicarbonate (HCO_3^-), which can subsequently lead to the formation of CO_2 (Snyder et al., 2009). Research by Vo et al. (2014) showed that sugarcane fertilization at 40–60% soil moisture levels increased CO_2 emissions, while using inorganic nitrogen fertilizers led to increased N_2O emissions. Similarly, Akiyama et al. (2004) reported that urea application in soils with 40–80% moisture content increased N_2O and NO emissions.

According to a study, the Mekong Delta is most susceptible to climate change (Ministry of Agriculture and Rural Development, 2022). Recent studies by Nguyen and Le (2023), and Zaman et al. (2021) show that proper compost management reduces GHG emissions. According to Nguyen and Le (2023), gardens following VietGAP standards and utilizing organic fertilizers emit lower levels of GHGs compared to conventionally managed orchards. Therefore, this study aims to assess how reusing agricultural byproducts, such as sugarcane compost, biogas residue, and Vermicompost, as organic fertilizers in rambutan cultivation, with a focus on reducing greenhouse gas emissions and promoting sustainable agriculture.

MATERIALS AND METHODS

Study site and experimental design

The field study was conducted at Phu Phung Commune, Cho Lach District, Ben Tre Province, Vietnam, on a rambutan (*Nephelium lappaceum L.*) orchard. The orchard was established on 17-year-old raised beds with rambutan trees of the same age. The soil in the experiment was classified as *(Endo Protho Thionic Gleysol)*, belonging to the group of deep potential acid sulfate soils, according to the FAO-UNESCO classification. This study used four treatments and three replications in a completely randomized block design (CRBD). Each plot contained two trees within a 60 m² area. The treatments were as follows: T1 (Control – Farmers' Practice): Application of inorganic fertilizers at 2.2 kg N, 1.5 kg P_2O_5, and 0.3 kg K_2O per tree per year; T2 (Sugarcane compost): Recommended inorganic fertilizer rates (1.5 kg N, 1.0 kg P_2O_5, and 1.7 kg K_2O per tree per year) combined with 18 kg/tree/year of sugarcane compost (30% moisture), applied once at the beginning of the growing season; T3 (Biogas residue): Same as T2, but using biogas residue; T4 (Vermicompost): Same as T2, but using Vermicompost. Inorganic fertilizers were applied based on the recommendations of Diczbalis (2002) and Vo et al. (2009), and they were divided into four applications per year. For gas sampling, plastic tubes were inserted into the soil at a distance of 70 cm from the tree base (as illustrated in Figure 1A). Each tube was sealed with a plastic container to collect gas emissions. Each treatment included four sampling tubes per replication, resulting in 48 tubes (4 tubes × 3 replications × 4 treatments).

Organic material characteristics

Organic matter (OM) used in the experiment originated from different locations in Vietnam: sugarcane bagasse was collected from a sugar factory in Vi Thanh district, Hau Giang province, and composted; biogas residue was collected from farmers in the study area, and Vermicompost was collected from farmers at the Delta Rice Institute,

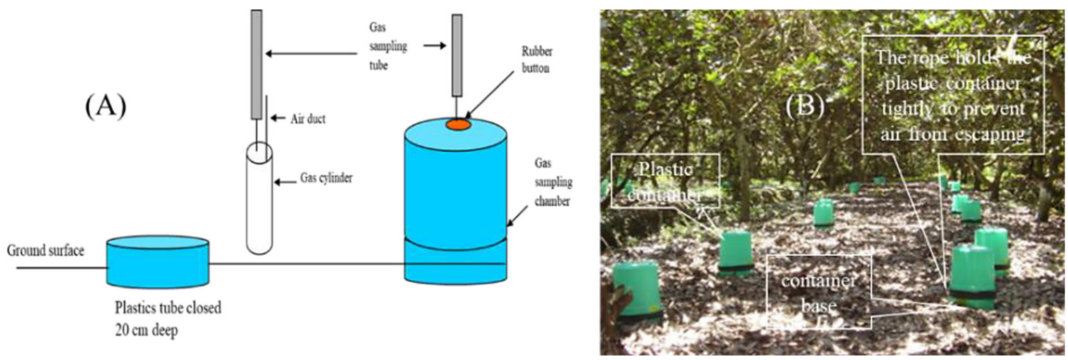

Figure 1. (A) Illustration of the placement of plastic chambers for gas sample collection, (B) positioning of the plastic chambers in the field

O Mon district, Can Tho city. The nutrient compositions were reported by Vo et al. (2014), and their initial properties are presented in Table 1.

Greenhouse gas sampling

Every gas collection device was made up of a base and a chamber. The plastic tanks used to construct the chambers have a surface area of 0.046 m² and a volume of 11.06 L. Before the experiment started, the bases were placed 20 cm into the ground (Figure 1B). Chambers were placed 70 cm from the base of each tree. The time frame for the gas sampling was 9:00 a.m. to 12:00 p.m. Samples were taken using 50 mL syringes and placed into sealed gas sampling bags one hour after the chambers were sealed. The sampling frequency alternated between three times per month and once per month, depending on the stage of crop development and environmental conditions. Gas sampling was conducted continuously over two years. Greenhouse gas concentrations (CO_2 and N_2O) were analyzed using a closed-loop gas chromatography system (Model SRI 8610C). CO_2 was measured using a flame ionization detector (FID) at 200 °C, while N_2O was detected using a Hayesep-N electron capture detector (ECD). The FID temperature was 350 °C, while the column chamber temperature was set at 60 °C.

Environmental factor measurements

During each gas survey, soil samples were taken at a depth of 20 cm to investigate environmental factors that may influence greenhouse gas emissions. Soil organic matter (SOM) was computed using the Walkley and Black (1934) method, and the amounts of ammonium (NH_4^+) and nitrate (NO_3^-) were measured using the procedures described by Bremner and Keeney (1966). Blake and Hartge's (1986) oven drying method dried the soil at 105 °C for 24 to 48 hours to estimate its gravimetric moisture content. The water-filled pore space (WFPS) was calculated using Equation 1:

$$WFPS\ (\%) = (Soil\ gravimetric\ water\ content\ \%)/(1\text{-}Soil\ bulk\ density/\ 2.65) \times 100\% \quad (1)$$

A thermometer was placed 10 cm into the earth for a temperature reading during gas sampling. The air temperature was measured with a thermometer during the sample process. The water level in the irrigation canal was also measured concurrently.

Flux and global warming potential (GWP) calculation

Equation 2 was utilized to compute the CO_2 and N_2O fluxes, adapted from Gao et al. (2014):

$$F = \left(\frac{273}{273} + T\right) \times \frac{M}{V} \times \frac{dc}{dt} \times H \times S \quad (2)$$

where: the gas flux is denoted by F (μg $N_2O \cdot m^{-2} \cdot h^{-1}$ or mg $CO_2 \cdot m^{-2} \cdot h^{-1}$), the average air temperature inside the chamber is T (°C), the molecular weight is M (44 $g \cdot mol^{-1}$ for both CO_2 and N_2O), the molar volume of gas at standard temperature and pressure is V (22.4 $L \cdot mol^{-1}$), the rate of change in gas concentration over time is dc/dt ($\mu L \cdot L^{-1}$ for N_2O, $mL \cdot L^{-1}$ for CO_2), the chamber volume is H, and the surface area is S.

The GWP was calculated using Equation 3, where the emission of N_2O was multiplied by its 100-year GWP factor of 298, as reported by the IPCC (2007):

$$GWP = RN_2O \times 298 + RCO_2 \times 1 \quad (3)$$

Data analysis

Microsoft Excel 2019 was utilized to process all of the gathered data. To perform the statistical analysis, SPSS 22.0 was used. The effects of various therapies were assessed using a one-way analysis of variance (ANOVA). At a 95% confidence level ($p < 0.05$), mean comparisons were performed using the least significant difference (LSD) test.

Table 1. Characteristics and nutritional composition of organic fertilizers

Organic fertilizers	pH_{H2O} (1:2.5)	Total N (%)	Avai. P (mg.kg-1)	Total C ($g.kg^{-1}$)	K^+	Ca^{2+}	Mg^{2+}
					$cmol_{(+)} \cdot kg^{-1}$		
Sugarcane compost	7.4	1.9	25	29.8	34	35	27
Biogas residue	6.5	1.45	55	37	36	6	27
Vermicompost	7.5	0.6	21	25.4	81	0.03	34

RESULTS AND DISCUSSION

Effect of fertilizer on CO_2 and N_2O emissions at the study site

Effect of fertilizer on CO_2 effluxes from the soil over time

According to the effluxes measurement data shown in Figure 2, fertilizer types had statistically different effects on soil CO_2 effluxes over time ($p < 0.05$). The vermicompost treatment exhibited fluctuating CO_2 efflux rates ranging from 0.12 to 1.65 $g.m^{-2}.h^{-1}$, in comparison, the biogas residue treatment ranged from -0.01 to 1.65 $g.m^{-2}.h^{-1}$, and the sugarcane compost treatment from -0.07 to 1.80 $g.m^{-2}.h^{-1}$. In contrast, the farmers' practice treatment showed relatively lower and more stable emissions, ranging from -0.10 to 0.86 $g.m^{-2}.h^{-1}$. On day 1 of cycle one and day 365 of cycle two, negative CO_2 effluxes were observed in all organic fertilizer treatments except Vermicompost. These negative values may be attributed to lower CO_2 concentrations in the fertilizer than the ambient air, whereas the vermicompost treatment likely showed positive effluxes due to microbial respiration. These trends were consistent with findings from the laboratory experiment. Specifically, in treatments with 140 and 200 mg N/kg of dry soil, CO_2 effluxes were lower than treatments with the same nitrogen levels supplemented with 0.8 g of sugarcane compost, as reported by (Vo et al., 2014). The results showed that the high carbon content in organic fertilizers supports the growth of bacteria, thereby accelerating the decomposition of organic matter and increasing CO_2 emissions. Using biochar in agriculture lowers N_2O emissions while raising CO_2 (Pastorelli et al., 2024; Ayaz et al., 2023). According to Anokye et al. (2024), Le et al. (2022), Shibata et al. (2016), Zhang et al. (2022), and Lal (2021), the addition of organic matter boosts microbial activity, which speeds up the decomposition of organic matter and, consequently, increases CO_2 effluxes into the soil. These results are in line with their findings.

According to Shibistova et al. (2009), applying organic fertilizers such as sugarcane compost, biogas residue, and Vermicompost at a rate of 18 kg per tree over two consecutive seasons significantly increased soil microbial biomass compared to treatments without organic fertilizer. The variation in CO_2 efflux rates among different fertilizer treatments can be attributed to differences in nutrient composition and the decomposition characteristics of each type. Biogas residue and Vermicompost, in particular, contain higher levels of readily decomposable organic compounds, which stimulate microbial respiration and accelerate the breakdown of organic matter, thereby increasing CO_2 efflux.

Effect of fertilizer on soil N_2O emission over time

The N_2O emission results in Figure 3 show the differences in emission rates among fertilizer treatments over time. The farmers' practice treatment exhibited the highest N_2O emissions, ranging from 0.32 to 19.49 $mg.m^{-2}.h^{-1}$. On the other hand, the sugarcane compost treatment consistently showed the lowest emissions, with a statistically significant difference ($p < 0.05$) between 0.17 and 13.75 $mg.m^{-2}.h^{-1}$. Between 0.26 and 12.74 $mg.m^{-2}.h^{-1}$

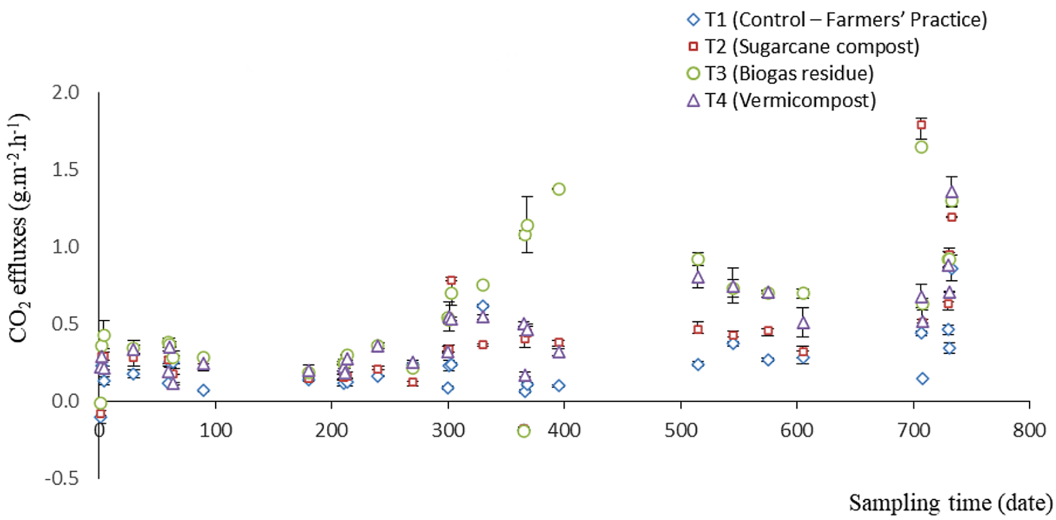

Figure 2. CO_2 effluxes over time

and 0.15 and 16.46 $mg.m^{-2}.h^{-1}$ were the intermediate emission values reported by the biogas residue and vermicompost treatments. Immediately after the start of cycle 1 and fertilization (organic and inorganic), the concentration of N_2O gas increased significantly in all treatments, then gradually decreased over time and continued to increase after each inorganic fertilizer application at 30, 90, and 303 days. In contrast, the CO_2 concentration measured in the soil was lower than the CO_2 concentration in the air, except for the vermicompost treatment, due to the intense microbial activity that increased CO_2 emissions. The same trend was also recorded in cycle 2, especially during inorganic fertilizer application on days 365, 395, 545, and 707. Sugarcane compost treatment maintained the lowest N_2O emissions throughout the experimental period. Compared with the findings of Petersen et al. (2010), where N_2O emissions over 240 days ranged from 392.9 to 629.6 $mg·m^{-2}.h^{-1}$ equivalent to a total emission of 1.6 to 3.9 $kg.ha^{-1}$ N_2O, our combined organic and inorganic fertilizer treatments resulted in lower emission levels.

According to Xu et al. (2024), initial organic fertilization may raise short-term N_2O emissions, but compared to mineral fertilization, it decreased cumulative N_2O and NO emissions by an average of 20% and 17%, respectively. Additionally, their analysis demonstrated that average N_2O emissions in pear orchards under organic fertilization were 67% greater than in orange orchards, underscoring the impact of crop variety and management techniques on greenhouse gas dynamics. According to Carter et al. (2011), N_2O emissions result from microbial nitrogen metabolism in the soil, and higher soil nitrogen content typically leads to increased N_2O release. Because different types of fertilizers include different amounts of readily degradable nitrogen, which affects microbial activity and the nitrification-denitrification processes, there may be changes in N_2O emissions between treatments. Zhang et al. (2022) and Shibata et al. (2016) also highlighted the possibility of using organic fertilizers in orchards instead of some mineral fertilizers to lower N_2O emissions successfully.

Correlation between environmental factors and CO_2 and N_2O emissions

Correlation between organic matter, soil temperature, air temperature, and CO_2 effluxes

Figure 4 shows that CO_2 effluxes from soil and soil organic matter, air temperature, and soil temperature are positively correlated, with R^2 coefficients of 0.82, 0.81, and 0.81, respectively. These robust relationships show that temperature and soil organic matter affect CO_2 effluxes. During the study period, soil temperature ranged from 25 to 28 °C, while air temperature fluctuated between 29 and 35 °C. Notably, on days 368 and 707, the soil temperature reached 28 °C, and the air temperature peaked at 35 °C, suggesting that high-temperature conditions may coincide with increased CO_2 effluxes. Soil organic matter content varied considerably over time, depending on the treatment. The lowest levels were observed in the farmers' practice treatment (1.7–14.9 mg $C.kg^{-1}$ soil), followed by the biogas residue treatment (2.4–32.7 mg $C.kg^{-1}$ soil), the vermicompost treatment (3.4–33.6 mg $C.kg^{-1}$ soil), and the highest levels were found in the sugarcane compost treatment (8.4–35.7 mg $C.kg^{-1}$ soil). These differences highlight the role of organic amendments in enriching soil carbon

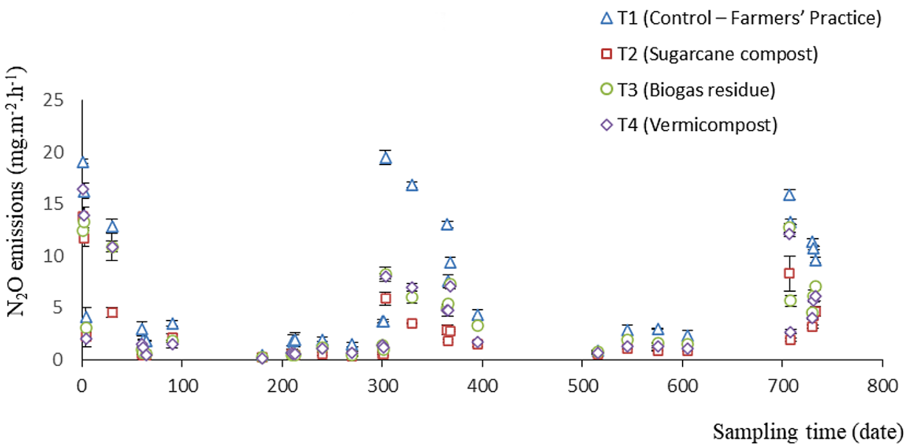

Figure 3. N_2O emissions over time

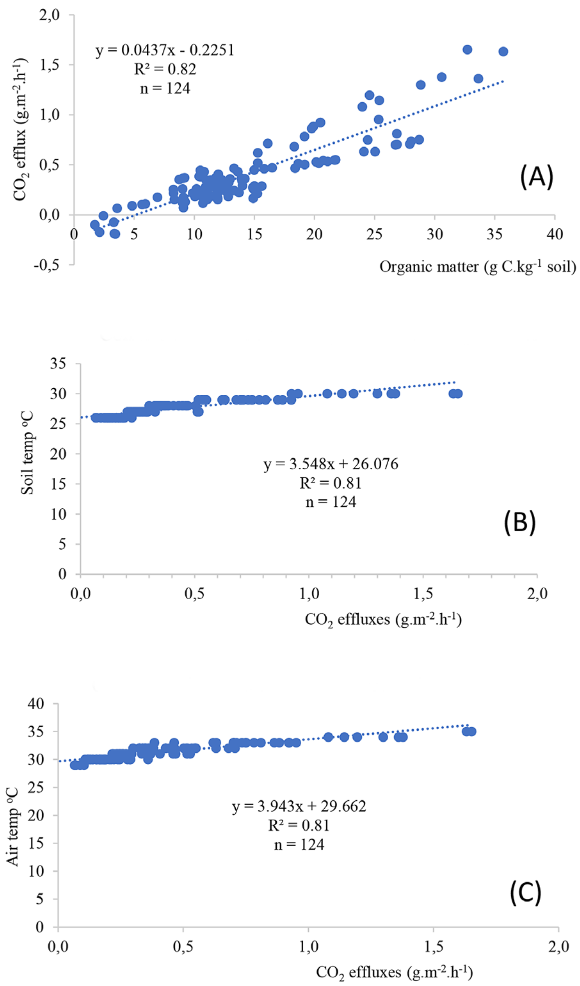

Figure 4. Correlation between (A) organic matter, (B) soil temperature, (C) air temperature, and CO_2 emissions

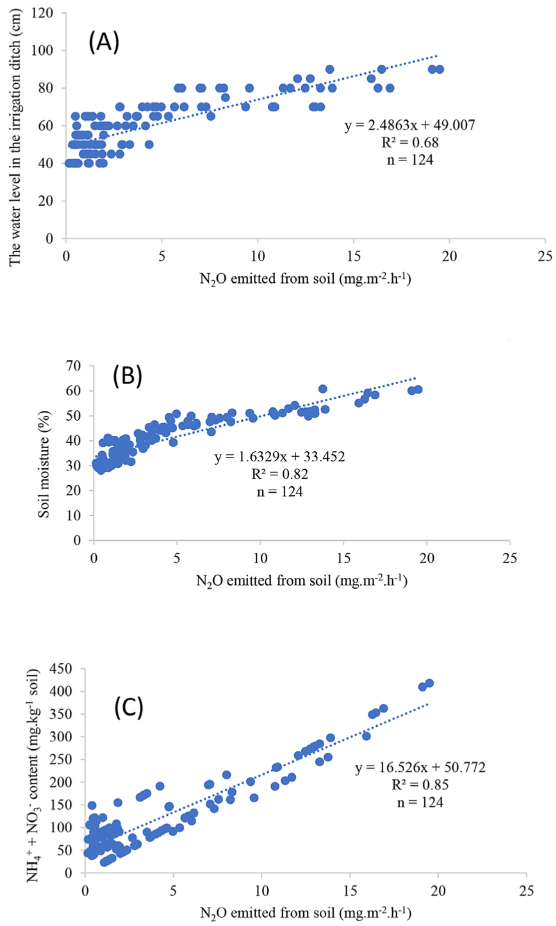

Figure 5. A) Correlation between irrigation ditch water level and N_2O emissionss, B) Correlation between irrigation ditch water level and N_2O emissions, C) Correlation between $NH_4^+ + NO_3^-$ and N_2O emission

content. These findings highlight the vital role of temperature and organic matter in CO_2 effluxes from soil. The findings of Song et al. (2019) indicated that in wetland environments with alternating dry and flooded conditions, CO_2 effluxes during spring were significantly higher than in winter ($P < 0.001$). A strong positive correlation was observed between CO_2 efflux rates and soil temperature in the 0–5 cm layer, with an R^2 value of 0.81. Various environmental factors strongly influence these microbial-driven transformations, including temperature, moisture, carbon availability, nutrient content, oxygen levels, and biological activity.

Correlation between $NH_4^+ + NO_3^-$ content, soil moisture, irrigation ditch water level, and N_2O emissions

The analysis of $NH_4^+ + NO_3^-$ content in the soil, presented in Figure 5A, shows significant differences among fertilizer treatments. The farmers' practice treatment, which involved the exclusive use of inorganic fertilizer, exhibited the highest range of mineral nitrogen content (190.2–418.2 mg·kg⁻¹ soil). Next are biogas residue (74.1–321.3 mg·kg⁻¹ soil), Vermicompost (60.34–269.6 mg·kg⁻¹ soil), and sugarcane compost treatments, which recorded the lowest values (53.2–194.1 mg·kg⁻¹ soil). Notably, $NH_4^+ + NO_3^-$ content was strongly correlated with soil N_2O emissions, with a correlation coefficient of $R^2 = 0.85$. These findings align with those of Galdos et al. (2023), who found that mineral nitrogen availability significantly influences N2O emissions. The study examined several ratios of sugarcane compost to mineral fertilizers and found a substantial positive link between the nitrogen fertilizer rate and cumulative N_2O emissions. Multivariate regression analysis, with an overall R^2

of 0.65, further demonstrated that soil chemical characteristics and climate variables substantially impacted cumulative N_2O emissions.

Figure 5B shows a non-linear correlation between N_2O emissions and soil moisture. N_2O emissions increased gradually when soil moisture ranged from 29% to 35%, but rose sharply once soil moisture exceeded approximately 45–50%. An R^2 value of 0.82 indicated a substantial association between soil moisture and N_2O emissions. The results showed that soil moisture in rambutan orchards during the experiment was within the optimal range for high N_2O emissions. These findings align with previous studies. Gleason et al. (2009) reported that peak N_2O emissions typically occurred when soil moisture was between 40% and 60%, and emissions dropped when moisture fell below 40% across all treatments. Similarly, Anokye et al. (2024), Akiyama et al. (2004), Linn and Doran (1984), and Silva et al. (2008) observed elevated total N_2O emissions under inorganic nitrogen fertilizer application when soil moisture ranged from 40% to 80%. These results have important implications for managing irrigation in orchards. By preventing excessive soil moisture, it is possible to limit N_2O emissions. In addition, adopting strategies such as balanced fertilization, nitrification inhibitors, and improved agricultural practices may help mitigate N_2O emissions, as Zhou et al. (2022) suggested.

The relationship between the irrigation ditch's water level and the soil's N_2O emissions is depicted in Figure 5C, with a correlation coefficient (R^2) of 0.68. The irrigation ditch's water level varied during the trial, from 40 cm (the lowest) to 90 cm (the highest), with an average level between 55 and 80 cm. Higher water levels were associated with increased N_2O emissions from the soil. This finding is consistent with the study by Berglund and Berglund (2010), which reported that lowering the water table exposes layers rich in easily decomposable organic matter, influencing CO_2 emissions. In contrast, increased soil moisture under higher water levels may promote conditions favorable for denitrification, leading to higher N_2O emissions, particularly when the water level is within the 40–80 cm range. According to Zhou et al. (2018), excess nitrogen from fertilizers and increased water availability can be denitrified, leading to N_2O emissions. Additionally, Song et al. (2019) suggested that in areas experiencing alternating dry and flooded conditions, winter N_2O emissions are influenced by temperature fluctuations. These results demonstrate how crucial irrigation water level control is to reduce N_2O emissions from agricultural soils.

GWP of fertilizers on rambutan orchard soil over time

Figure 6 shows that different fertilizer types significantly affect GWP. The farmer's treatment, applying only high-nitrogen inorganic fertilizers, resulted in the highest greenhouse gas emissions, ranging from 0.51 to 6.66 g CO_2-eq·m^{-2}·h^{-1}. Peak emissions were observed at specific fertilizer application times: day 1 (5.59 g CO_2-eq·m^{-2}·h^{-1}), day 303 (6.05 g CO_2-eq·m^{-2}·h^{-1}), and day 330 (6.66 g CO_2-eq·m^{-2}·h^{-1}). In contrast, treatments using sugarcane compost, biogas residue, and Vermicompost significantly reduced CO_2-eq emissions compared to the Farmers' practice. Among these, the sugarcane compost treatment recorded the lowest emissions (0.22–4.02 g CO_2-eq·m^{-2}·h^{-1}),

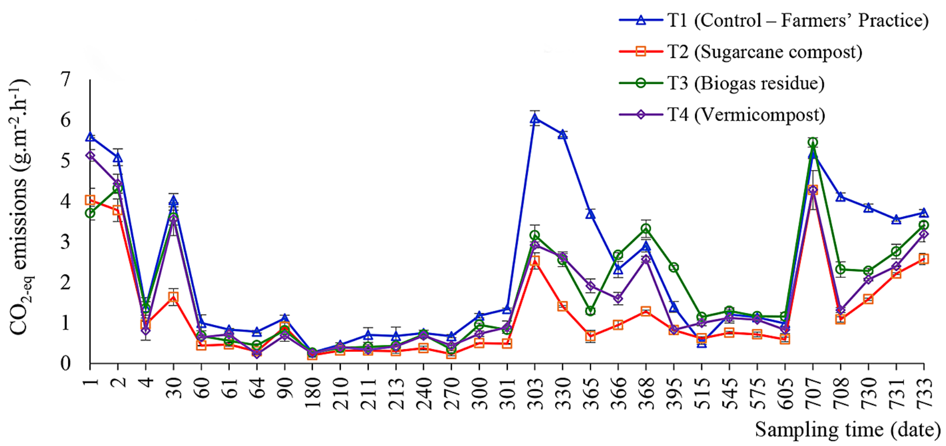

Figure 6. GWP of fertilizers on rambutan orchard soil

with statistically significant differences ($p < 0.05$). These field results align with laboratory findings reported by Vo et al. (2014), which showed that inorganic fertilizers significantly increased N_2O emissions, resulting in a 26.1–71.6% higher CO_2-eq total compared to organic fertilizer treatments. Similarly, Anokye et al. (2024) found that mineral fertilizers produced the highest GWP values, reaching 14.70×10^5 and 13.56×10^5 kg CO_2-eq $ha^{-1} \cdot year^{-1}$ in humid and dry ecozones, respectively. Furthermore, compared with the findings of Petersen et al. (2010), where the N_2O emission rate over 240 days ranged from 117.07 to 187.3 g CO_2-eq$\cdot m^{-2} \cdot h^{-1}$, the emission levels recorded in this study were considerably lower. According to Nguyen and Le (2023), gardens following VietGAP standards and utilizing organic fertilizers emit lower levels of GHGs compared to conventionally managed orchards. In addition to reducing emissions, organic fertilizer application also improved soil moisture and texture, creating more favorable conditions for microbial activity, which further contributed to mitigating greenhouse gas emissions (Wang et al., 2022).

CONCLUSIONS

In comparison to the farmers' practice, the treatments that administered 18 kg of organic fertilizer per tree along with inorganic fertilizer (1.5 kilogram N, 1.0 kg P_2O_5, and 1.7 kg K_2O per tree per year) had the most significant CO_2 emissions in the soil of rambutan orchards. N_2O emissions, on the other hand, peaked with the Farmers' Practice treatment.

Soil organic matter and CO_2 emissions were shown to be strongly positively correlated ($R^2 = 0.82$), as were soil temperature ($R^2 = 0.81$) and air temperature ($R^2 = 0.81$). Meanwhile, N_2O emissions were closely associated with ($NH_4^+ + NO_3^-$) concentrations ($R^2 = 0.85$), soil moisture ($R^2 = 0.82$), and water level in the irrigation ditch ($R^2 = 0.68$). Farmers' practices had the highest GWP, ranging from 0.51 to 6.66 g CO_2-eq$\cdot m^{-2} \cdot h^{-1}$. Followed by treatments with biogas residue (0.45–5.45 g CO_2-eq$\cdot m^{-2} \cdot h^{-1}$), Vermicompost (0.23–5.13 g CO_2-eq$\cdot m^{-2} \cdot h^{-1}$), and the lowest in sugarcane compost treatment (0.22 – 4.02 g CO_2-eq$\cdot m^{-2} \cdot h^{-1}$).

The impacts of Vermicompost, sugarcane compost, and biogas residue on soil fertility, rambutan yield, quality, and their influence on greenhouse gas emissions need further investigation.

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