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RESEARCH ARTICLE

INTERACTIVE NUTRIENT MANAGEMENT: COMPOST AND NITROGEN EFFECTS ON SUBTROPICAL SOIL EMISSIONS

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Abstract

Overproduction of greenhouse gases (GHGs) by agricultural soils is a critical environmental issue, especially in subtropical farming systems, where mixed organic and inorganic nitrogen (N) management is commonly used to maintain soil fertility. A 3×3 factorial design was arranged using nine treatments in a controlled laboratory incubation experiment, using three compost rates (C_0-0, C_1-30, and C_2- 60 T ha^{-1}) and three N fertilizer rates (N_0-0, N_1-60, and N_2-120 kg N ha^{-1}). This study aimed to determine the short-term impacts of different rates of inorganic N fertilizers (N_0: 0, N_1: recommended, N_2: double recommended) and compost application levels (C_0: no compost, C_1: low compost, C_2: high compost) on N_2O and CO_2 emissions on a Vertisol soil collected at Gatton, Queensland, Australia, under controlled incubation conditions. The cumulative N_2O and CO_2 emissions during the incubation period were also measured and given as kg N ha^{-1} and Mg C ha$^{-1,}$ respectively. Findings indicated that the application of inorganic N fertilizer alone did not have any significant influence on the emissions of N_2O (N_0C_0: 17.13, N_1C_0: 54.77, N_2C_0: 88.75 kg N ha^{-1}; $p > 0.05$), but the co-application of compost and inorganic N had a considerable effect on the emissions of N_2O, with the greatest reduction being observed in the N_2C_1 treatment (1031.96 ± 124 kg N ha^{-1}). The addition of compost also increased CO_2 emissions across all N levels, with the cumulative CO_2 efflux maximized at the N_1C_2 level (69.5 ± 13.4 Mg C ha-^{1}) due to increased microbial heterotrophic respiration and priming effects. It is interesting to note that high rates of inorganic N application, combined with moderate levels of compost application (N_2C_1), inhibited CO_2 emissions, indicating that nitrogen suppressed microbial decomposition activity. The results of this study suggest that the best strategy to reduce short-term GHG emissions while maintaining soil health and mineralisation potential is to co-apply 60 t ha^{-1} compost and 120 kg N ha^{-1} fertilizer (N_2C_2). These results indicate that the combined use of compost and inorganic N fertilizers significantly increased GHG emissions in Vertisol soils, highlighting the importance of optimizing organic-inorganic N input ratios to reduce environmental trade-offs whilst preserving the agronomic productivity of subtropical crop systems. The long-term impacts and field-scale validation of these results should be investigated in future research.

Keywords: Compost, Greenhouse gas emissions, Nitrogen fertilizer, Subtropical, Vertisol

INTRODUCTION

Agriculture is a key land-use practice across the globe (Aznar-Sánchez *et al*., 2019). Around 1.2 to 1.5 billion hectares are croplands of all the Earth's land, while another 3.5 billion hectares are used for pasture. To accommodate the demands of exponential population growth, synthetic fertilizer use has become more prevalent due to its high solubility, which enables easy nutrient uptake by plants and facilitates storage and handling (FAO, 2019). Global fertilizer projections also indicated an increase in nitrogen fertilizer consumption to up to 106 million tonnes by 2025. Around 60% of global N fertilizer is used in cereal production (Mueller *et al*., 2014), and global

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cereal demand is expected to increase by 60% over the next 40 years (Tian *et al*., 2021). Reay *et al*. (2012) reported that agricultural N_2O emissions had increased globally by17% from 1990 to 2005. By 2030, there will be a 35–60% increase in global agricultural N_2O emissions (Bennetzen *et al*., 2016), and emissions are expected to double by 2050 due to increased N fertilizer inputs unless mitigation strategies are implemented (Davidson *et al*., 2014).

Agricultural fertilizer use has reduced nitrogen limitations in cropland and noticeably increased crop yields and soil fertility over the past century (Lu & Tian, 2017). It has also contributed extensively to increasing agricultural productivity and decreasing hunger worldwide (Lu & Tian, 2017). Alternatively, excessive fertilizer use has been shown to cause numerous environmental problems, such as air pollution, water eutrophication, soil acidification, and degradation (Tian *et al*., 2015).

Global N fertilizer usage has increased from 11.3 Tg N yr^{-1} (in 1961) to 107.6 Tg N yr^{-1}(in 2013), and at the same time, emissions from synthetic N fertilizers have increased more than ninefold, from 0.07 in 1951 to 0.68 Gt CO_2 eq yr^{-1}in 2010 (Tubiello *et al*., 2014). Agricultural soils are a key anthropogenic source of N_2O, accounting for 50% of global human-derived N_2O emissions. (Syakila and Kroeze, 2011). Various experiments on N_2O emissions from agricultural soils have demonstrated a strong positive correlation between N fertilizer application and N_2O emissions (Shcherbak *et al*., 2014). N_2O is generated as an obligate intermediate or as a by-product of nitrification and denitrification, which are two microbial-mediated mechanisms (Storch *et al*., 2025), and they depend on mineral N (ammonia and nitrate) as their substrate (Ahmed, 2025).

Significantly higher N_2O losses can be achieved by denitrification than by nitrification. In denitrification, N_2O is produced when conditions are not conducive to completing the process. Under unfavourable conditions, a higher proportion of nitrified N can be lost as N_2O (Han *et al.,*2024). The N_2O production process is significantly accelerated in agricultural soils, due to the addition of quickly nitrifiable forms of N (N fertilizers such as urea) along with soil aeration due to tillage (Liyanage, 2019).

OA has been proposed as an effective option to improve soil fertility while reducing environmental pollution. The application of OA has indisputable benefits to improve soil fertility while sequestering carbon in soils (Xu *et al*., 2022). The addition of OA has been shown to improve soil health while enhancing the physical, chemical, electrical conductivity, and biological properties of soil (Thangarajan *et al*., 2013). OA not only serves as a source of nutrients but also affects microbial activity and the soil organic pool, which together regulate the rate of N_2O production (Bamdad, *et al*., 2022). OA can also decrease the bulk density of the soil, which is essential for a healthy soil (Aytenew *et al*., 2020). The application rates of OA are several times higher than those of synthetic N fertilizer, yet wide-ranging benefits for agricultural soils have been reported worldwide from OA application (Quilty and Cattle, 2011).

The application of OA alone cannot fulfil the plant N (Celestina *et al.,* 2019). Hence, combining compost with synthetic fertilizer that accurately meets plant N demand could be an optimal strategy for sustainable crop production. The combined application of synthetic N fertilizer with OA has improved N fertilizer efficiency and reduced synthetic fertilizer use by 40% while maintaining the same tomato quality (Hernández *et al*., 2014). The application of compost (a widely used type of OA) to soils and its impact on N_2O emissions can be observed in two different pathways.

As the first pathway, compost can reduce N_2O emissions by promoting soil N immobilisation, reducing the mineral N substrates available for nitrification and denitrification (Ding *et al.* 2013), or as the second pathway, the application of compost will potentially increase N_2O emissions by increasing dissolved organic carbon (DOC), which stimulates soil microbial activity (Zhu-Barker *et al.*, 2015).

Although the agronomic benefits of OAs have been the focus of numerous studies (Thangarajan *et al.*, 2013; Scotti *et al.,* 2015; Urra *et al.*, 2019), there is little complementary information on the interaction of OAs with synthetic fertilizers on the immobilisation or mineralisation of labile N, and the subsequent contribution to GHG emissions. We hypothesised that the rate of mineralisation of labile C and N compounds in compost, in concert with N fertilization, will be largely driven by the C: N ratio of the inputs, with N_2O emissions increasing above a certain threshold.

In the low-carbon soils prevalent in the tropics, additional carbon available even from supposedly "stabilised" material, such as composts, might still be sufficient to increase denitrification and, subsequently, N_2O emissions. This study aimed to determine the short-term impacts of different rates of inorganic N fertilizers and compost application levels on N_2O and CO_2 emissions and mineral N in a Vertisol soil collected at Gatton, Queensland, Australia, under controlled incubation conditions.

MATERIALS AND METHODS

Experimental design

The effects of compost and inorganic nitrogen (N) fertilizer on N_2O and CO_2 emissions were investigated in a factorial incubation experiment of a Vertisol soil. The experiment involved two factors: one factor was the urban -derived compost used at three levels (C_0: 0 t ha $^{-1}$, C_1: low rate, C_2: high rate), and the other factor was inorganic N fertilizer used at three levels (N_0: 0 kg N ha $^{-1}$, N_1: recommended rate, N_2: double the recommended rate). All treatment combinations were repeated 4 times (4 replicates), resulting in a total of 36 experimental units per sampling event.

To follow 3 destructive sampling events at set times during the five-week incubation period, three independent sets of 36 experimental units were prepared at the beginning of the experiment, resulting in 108 experimental units (9 treatments x 4 replicates x 3 destructive sampling events). During the specified sampling events, a single set of 36 experimental units was destructively sampled at the specified time for soil assessment, yielding time-point measurements from independent sampling of undisturbed samples from the same units.

Experimental units were Vertisol soil obtained in Gatton, Queensland, Australia (27.56° S, 152.27° E), with a texture ranging from clay loam to silty clay, and baseline soil properties of 2.1% organic carbon and 0.9% total nitrogen (Table 1). All the samples were maintained in a controlled laboratory environment at 25 °C throughout the experiment.

Table 1: Selected characteristics of soil and compost used for the experiment

	Soil 0-20 cm	Compost
pH	7.8	6.8
CEC (cmol kg^{-1})	43.9	31.9
Total C %	2.1	23.5
Total N %	0.9	1.9
CN ratio	23	12.4
Clay %	43.7	
Silt %	41.0	
Sand %	14.3	

Soil and compost preparation

Three rates of fertilizer equivalent to 0 (N_0), 60 kg N ha^{-1} (N_1), and 120 kg N ha^{-1} (N_2) were applied, along with three rates of urban-derived compost (made using green waste), equivalent to 0 (C_0),30 T ha^{-1} (C_1), and 60 T ha^{-1} (C_2).

Measured amounts of compost (0 g, 6 g, and 12 g per core) were applied at the selected compost rates. One hundred and seventy-five grams of clay loam soil was thoroughly mixed with compost samples. The mixture was incubated in sealed 1 L glass jars after being repacked into a 15 cm-high by 5 cm-diameter PVC cylindrical pipe (cores) to a bulk density of 1.3. Before applying N fertilizer in the form of ammonium Sulphate $(NH_4)_2SO_4$, the soil was pre-incubated for seven days. Following pre-incubation, soil moisture levels for all treatments were set to 60%, and consistent soil moisture conditions were maintained throughout the experiment.

Incubation setup and gas sampling

The CO_2 flux rate and the rate of nitrous oxide (N_2O) were recorded on days 1, 3, 7, 14, 21, 28, 29, 32, and 36 after the incubation experiment was initiated. To measure the gas flux, sealed borosilicate glass incubation jars with airtight rubber septa lids were used to sample the headspace gases. Jars were closed gas-tight at each sampling event and remained sealed during the incubation period. Vitally, the jars were left open between sampling intervals to promote the free exchange of gases between the jar and the ambient atmosphere and to avoid the buildup of CO_2 and N_2O and the development of artificial anaerobic conditions (Rochette and Eriksen-Hamel, 2008).

This methodology ensured that aerobic soil conditions remained stable between sampling intervals and that measured gas fluxes indicated realistic emission rates. Using a syringe, 20 mL headspace samples were periodically collected from the incubation jars and placed in 12 mL evacuated vials (Exetainer, Labco, UK). After each gas sample, the jars were opened to allow the gas concentrations to return to normal. A Shimadzu GC-2014 gas chromatograph was used to analyze N_2O and CO_2 fluxes.

Soil mineral N analysis

On days 0, 7, 28, and 36, soils were destructively sampled to assess changes in mineral N content. A 1:5 soil to KCl solution was used to analyse NH_4^{+}- N and NO_3^{-} - N, and an AQ_2^{+} SEAL Analytical, USA, was used to measure the extract. N_2O and CO_2 were measured after 28 days, when all of the remaining soil cores were saturated to mimic a period of intense rainfall. Mineral N (ammonium-N and nitrate-N) at time 0 was subtracted from the mineral N in the soil sample to determine mineralizable N after incubation.

Statistical analysis

Linear interpolation was commonly used as a gap-filling technique for N_2O flux data, in which data gaps between sequential measurement days were filled by connecting the points with straight lines to obtain cumulative N_2O fluxes for each chamber. Fluxes were modified to account for the site's air temperature and pressure and expressed on an elemental weight basis. Using the coefficient of determination (r^2), flux quality control was performed, and fluxes with $r^2 < 0.80$ were rejected to accurately predict fluxes during periods of high variability, such as after fertilizer application or rainfall events.

The primary response variables have been statistically compared across treatments of cumulative N_2O and CO_2 flux during the 36-day incubation period. The R statistical computing environment was used to perform all statistical analyses (R Core Team, 2023). Two-way analysis of variance (ANOVA) was used to determine the influence of compost rate, rate of inorganic N fertilizer, and the product of these two factors on N_2O and CO_2 emissions with the compost level and N fertilizer rate as factors and Tukey Honestly Significant Difference (HSD) test at the significance level 0.05 was performed to determine specific treatment effects that differed significantly, and to control the family-wise error rate.

RESULTS

Effect of compost and Nitrogen fertilizer rates on cumulative N_2O and CO_2 emissions

The highest cumulative N_2O emissions measured over the 36-day incubation were from the fertilized treatments at the moderate (30 T ha^{-1}) compost application rate, with emissions of 1032 and 897 kg N ha^{-1} for the N_2C_1 and N_1C_1 treatments, respectively, while the lowest emissions (17 kg N ha^{-1}) were from the C_0N_0 treatment.

Compared to the control (N_0C_0), statistically higher losses ($p < 0.05$) were found in the N_1C_1, N_2C_1, and N_2C_2 treatments. Increasing the compost rate to the highest level (60 T ha^{-1}) has reduced N_2O emissions by 57% and 68% in the N_2 and N_1 treatments, respectively (Table 2).

Table 2: Effect of N and compost mix application on cumulative N_2O and CO_2 emission after incubation from a Vertisol (Gatton, Australia)

Treatments	Cumulative N_2O (kg N ha^{-1})	Cumulative CO_2 (Mg C ha^{-1})
N_0C_0	17.13 ± 9.95^a	3.7 ± 0.9^a
N_0C_1	91.07 ± 45.3^a	48.4 ± 6.0^b
N_0C_2	102.84 ± 72.27^a	56.2 ± 28.2^c
N_1C_0	54.77 ± 14.69^a	9.8 ± 2.1^a
N_1C_1	897.30 ± 15.72^b	47.4 ± 14.3^d
N_1C_2	321.53 ± 29.79^a	69.5 ± 13.4^e
N_2C_0	88.75 ± 44.063^a	7.4 ± 5.6^a
N_2C_1	1031.96 ± 124.00^c	17.8 ± 5.8^a
N_2C_2	496.78 ± 92.525^d	43.7 ± 2.2^f

Letters indicate significant differences ($p < 0.05$) among treatments

Interactive effects were pronounced on cumulative N_2O and CO_2 emissions at the rates of compost application and inorganic nitrogen (N) fertilizer during the incubation period. Without compost (C_0), cumulative N_2O emissions were relatively low, regardless of the amount of nitrogen applied (N_0C_0: 17.13, N_1C_0: 54.77, and N_2C_0: 88.75 kg N ha^{-1}). There were no statistically significant differences among the treatment options ($p > 0.05$), indicating that inorganic N fertilizer in the absence of compost was not a strong inducer of N_2O emissions.

The N_2O emissions, however, were significantly enhanced when compost was used with inorganic N fertilizer, especially when the applied N level was high. The cumulative N_2O emission in the N_2C_1 treatment (1031.96 ± 124.00 kg N ha^{-1}) was high compared to all other treatments ($p < 0.05$), followed by the N_1C_1 (897.30 ± 15.72 kg N ha^{-1}).

This accentuated rise in the flux of N_2O under combined organic and inorganic N inputs has probably been attributed to an increase in the rate of microbial denitrification, which is stimulated by the concurrent supply of labile carbon substrates from compost and elevated inorganic N levels (Velthof *et al.*, 2003). It has been observed that the heavy clay matrix of the Vertisol supports the development of anaerobic microsites that can further enhance denitrification under moist conditions (Brady & Weil, 2017), which could be the cause of enhanced emissions when compost and Ns are heavy. It is noteworthy that N_2C_2 (496.78 ± 92.52 kg N ha^{-1}) had much lower N_2O emissions compared to N_2C_1 ($p > 0.05$), which may be explained by the fact that the higher the compost application rates, the more microbial N was immobilized and, as a result, the less mineral N was available to be denitrified (Geisseler & Horwath, 2014; Rothardt *et al*., 2021) or by the fact that increased organic matter.

A significantly different pattern was observed for Cumulative CO_2 emissions. No compost treatments (C_0) yielded relatively steady CO_2 emissions irrespective of the rate of N fertilizer (N_0C_0: 3.7, N_1C_0: 9.8 and N_2C_0: 7.4 Mg C ha $^{-1}$), and there was no significant difference between them ($p > 0.05$) (Table 2). Conversely, the addition of compost had an enormous effect on soil CO_2 emissions across all N levels, indicating that intense microbial heterotrophic respiration was driven by the mineralisation of easily decomposable organic carbon in the compost (Kuzyakov, 2010). N_1C_2 (69.5 ± 13.4 Mg C ha $^{-1}$) recorded the highest cumulative CO_2 emission, which was significantly different from all the other treatments, followed by N_0C_2 (56.2 ± 28.2 Mg C ha $^{-1}$) and N_0C_1 (48.4 ± 6.0 Mg C ha $^{-1}$).

These findings are correlated with the already established priming effect, whereby the addition of fresh organic material promotes the breakdown of the added and native soil organic matter due to increased microbial activity (Chen *et al*., 2014). Interestingly, N_2C_1 (17.8 ± 5.8 Mg C ha^{-1}) did not show significant differences with no-compost treatments, which could indicate that high inorganic N application rates decreased microbial breakdown of organic matter due either to the inhibition of ligninolytic enzyme activities by nitrogen (Waldrop *et al*., 2004) or to stoichiometric imbalances existing in the soil microbial community that slowed the process of organic matter breakdown (Mooshammer *et al*., 2014).

The highest mineralizable N, 224.9 kg ha^{-1}, was also observed, corresponding to the higher N_2O emissions in N_2C_1 treatment, while N_0C_0 treatment obtained the lowest 20.8 kg ha^{-1} during 7 days after fertilizer application (Table 3). Similar to N_2O emissions, at the same N level, the highest mineralizable N was obtained from medium C (C_1) treatments (N_1C_1 and N_2C_1), not from the highest C (C_2) treatments, indicating a decline in N_2O emissions after the addition of higher C levels.

Table 3: Day 7, 28 and 36 potentially mineralizable nitrogen (PMN)-(kg ha^{-1}) from the nitrogen X compost factorial experiment of three different N rates, 0 (N_0), 60 (N_1) and 120 (N_2) kg N ha^{-1}, and three compost rates, 0 (C_0), 30 (C_1), 60 (C_2) T ha^{-1}

Day	Treatment								
	N_0C_0	N_0C_1	N_0C_2	N_1C_0	N_1C_1	N_1C_2	N_2C_0	N_2C_1	N_2C2
Day 7	20.8	32.8	60.9	89.4	146.3	130.8	155.2	224.9	212.3
Day 28	27.3	42.9	37.3	71.7	72.7	62.0	145.9	152.1	127.6
Day 36	34.1	30.5	30.8	84.9	47.3	31.1	97.9	94.4	49.2

From day 7 to 28, daily mineralizable N showed a gradual decline in all N levels of the three C levels tested above (Table 3).

After the addition of water to saturate the cores on day 28, daily N_2O emissions declined in all N levels of the three C levels tested above by 27% to 45%

(Figure 1).During the first seven days after water addition (60% of soil moisture levels).

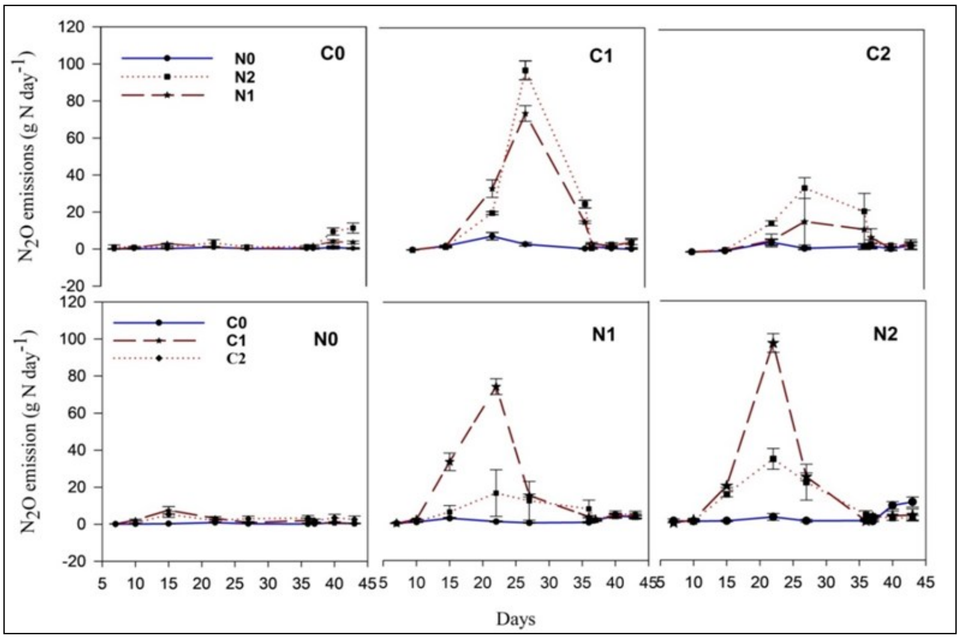

Figure 1: Change in daily N_2O emission over time from the nitrogen X compost factorial, presented as the effect of increasing N rate (0 (N_0), 60 (N_1) and 120 (N_2) kg N ha^{-1}) on each compost rate (top 3 graphs), and the effect of increasing compost rate (0 (C_0), 30 (C_1), 60 (C_2) T ha^{-1}) at the three N rates (bottom 3 graphs)

Daily N_2O emissions increased slightly to 12 g N_2O-N ha^{-1} day^{-1}. Daily CO_2 emissions followed a similar pattern, with reductions of 63% to 81% (Figure 2).

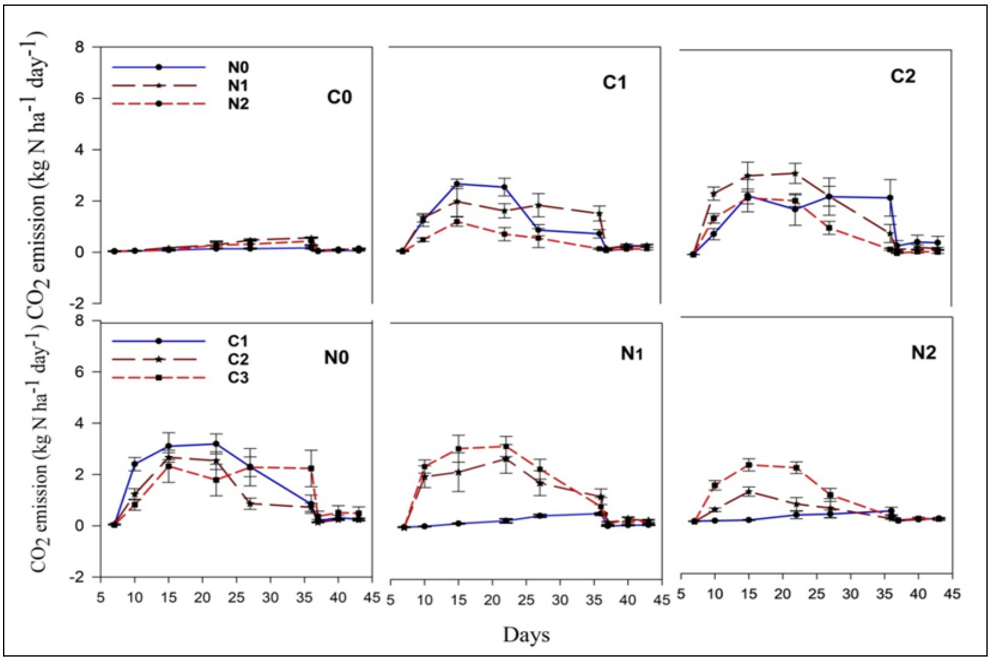

Figure 2: Changes in daily CO_2 emission over time from the nitrogen X compost factorial, presented as the effect of increasing N rate (0 (N_0), 60 (N_1) and 120 (N_2) kg N ha^{-1}) on each compost application rate (top 3 graphs), and the effect of increasing compost rate (0 (C_0), 30 (C_1), 60 (C_2) T ha^{-1}) at the three N rates (bottom 3 graphs)

After the application of compost and $(NH_4)_2SO_4$, soil NO_3^- and NH_4^+ concentrations exceeded the control in all treatments during the first seven days. Higher NH_4^+-N concentrations were observed in treatments receiving more fertilizer (Figure 3).The N_2C_2 treatment had the highest soil NH_4^+ concentration (179.4 kg N ha^{-1}) on day 7, and across all treatments, NH_4^+ levels declined to 20 kg N ha^{-1} by day 28.

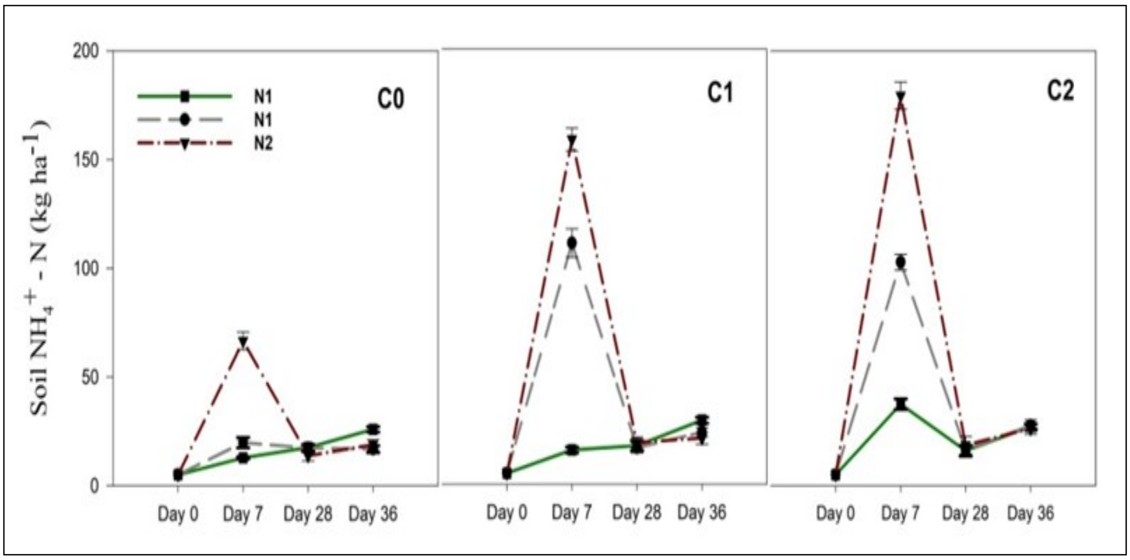

Figure 3: Changes in soil ammonium concentration of a Vertisol during incubation with or without compost treatments and N fertilizer

When considering soil NO_3^- concentrations, a gradual increase was observed up to 28 days (Figure 4), and then plateaued after saturation, at approximately 20 kg N ha^{-1}. Nitrate content increased over the first 28 days, with the highest NO_3^--N concentration (137.9 kg N ha^{-1}) observed in the N_2C_1 treatment. After saturation of the soil cores on day 28 of the incubation, soil NO_3^- concentration showed a rapid decline.

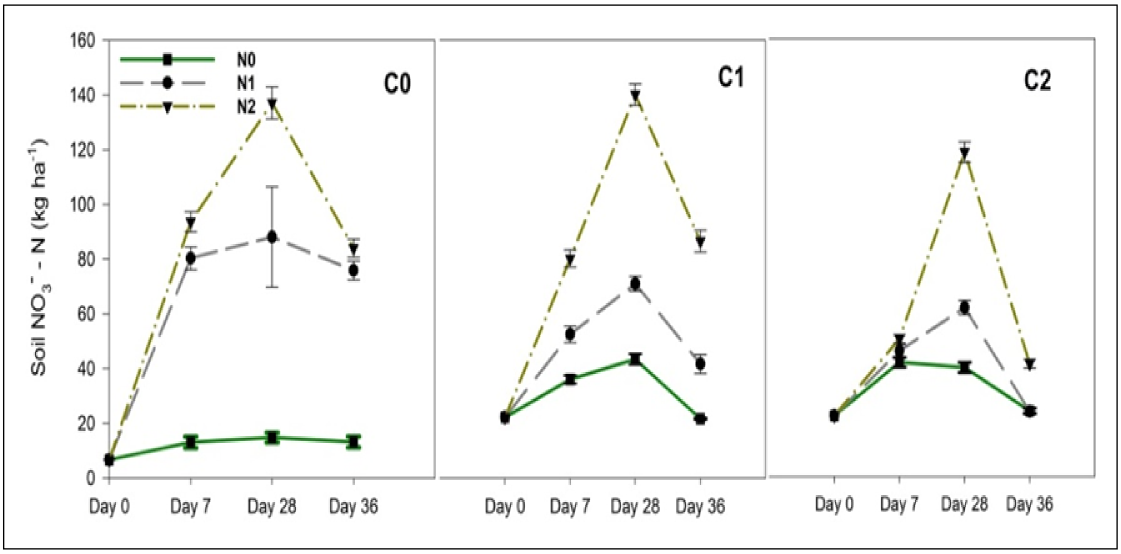

Figure 4: Variation in soil nitrate concentration of a Vertisol during incubation with or without compost treatments and N fertilizer

Potentially mineralizable nitrogen rates increased before the day 28 wetting event only in the control (N_0C_0) and N_0C_1 treatments. In contrast, mineralisation rates in all other treatments declined between days 7 and 28 (Table 3 and Figure 5). These declines were highest in the N_2 + compost treatments and lowest in the C_0 treatments. Typically, N application had a much greater influence on PMN than the compost rate. All treatments decreased sharply after the day 28 wetting event, except the control and N_1C_0 treatment, which increased marginally (Figure 5).

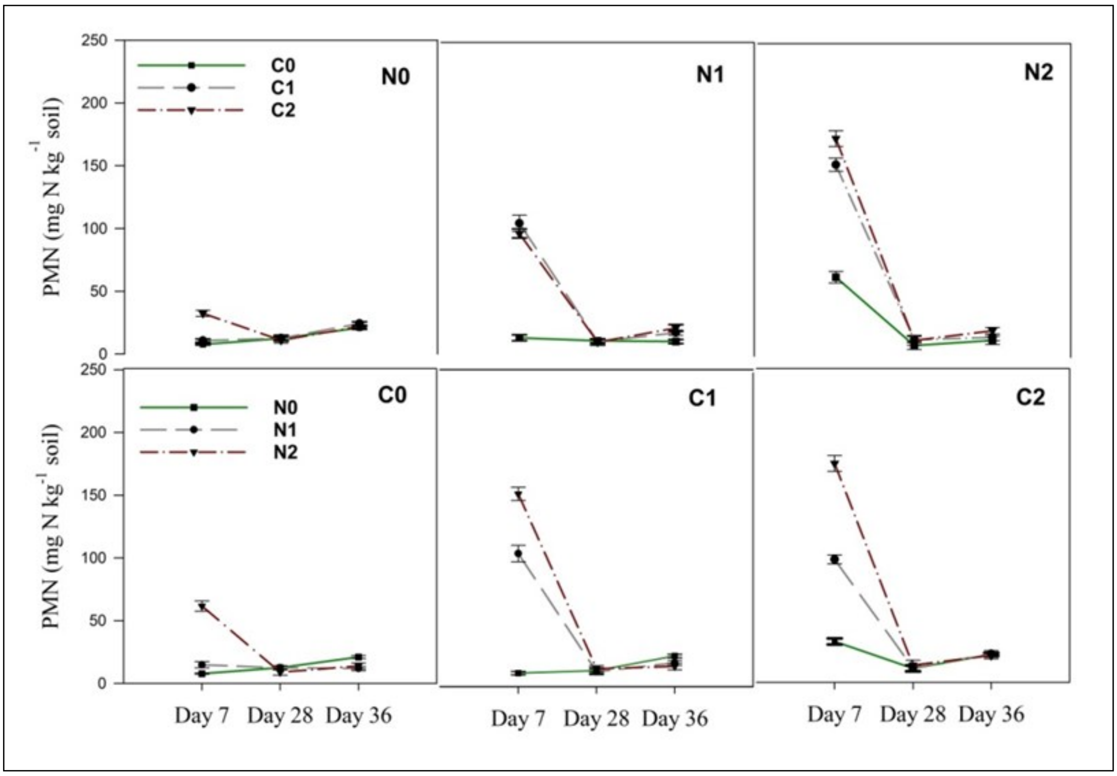

Figure 5: Changes in potentially mineralizable nitrogen (PMN) over time from the nitrogen X compost factorial, presented as, the effect of increasing compost rate (0 (C_0), 30 (C_1), 60 (C_2) T ha^{-1}) at the three N rates (top 3 graphs), and the effect of increasing N rate (0 (N_0), 60 (N_1) and 120 (N_2) kg N ha^{-1}) on each compost application rate (top 3 graphs)

DISCUSSION

This study provides a comprehensive understanding of how different compost rates and nitrogen (N) fertilizer rates influence greenhouse gas emissions, soil N dynamics, and nitrogen mineralisation. The interactive effects of organic and inorganic N inputs are further moulded by soil moisture and subsequent water saturation.

The impact of compost and N fertilizer on N_2O emissions and mineralizable Nitrogen

The findings of the current experiment indicated that inorganic N (N) fertilizer used alone had a relatively small effect on cumulative N_2O emissions in the Vertisol soil, which did not indicate any statistically significant differences among the treatments (N_0C_0 17.13 kg N ha^{-1}, N_1C_0 54.77 kg N ha^{-1} and N_2C_0 88.75 kg N ha^{-1}) (Table 2). These results are generally corroborated by the fact that the mineral N fertilizer production of N_2O is strongly mediated by the availability of labile organic carbon, which serves as an electron donor to denitrifying microorganisms (Butterbach-Bahl *et al*., 2013). Without carbon sources in compost, substrate limitation might have constrained the soil microbial community's ability to maintain high denitrification rates, even in the presence of high inorganic N availability. Wong *et al.* (2023) supported this assumption by demonstrating that soil N_2O fluxes were strongly regulated by the product of mineral N levels and water-filled pore space, and that organic carbon inputs had a significant modifying effect.

Co-application of compost and inorganic N fertilizer significantly increased N_2O emissions across all N rates, with reactions most intense at intermediate and high compost levels. The N_2C_1 (1031.96 ± 124 kg N ha^{-1}) treatment had the highest cumulative N_2O emission among all treatments ($p < 0.05$), followed by N_1C_1 (897.30 ± 15.72 kg N ha-^{1}). Such amplified N_2O emissions during combined organic and inorganic N applications are consistent with the long-established fact that denitrification activity is co-limiting for both mineral N and labile carbon substrates, and that the associated release of both factors provides the optimum environment for N_2O generation (Butterbach-Bahl *et al*., 2013). Heterotrophic microbial activity is activated by the supply of readily decomposable organic carbon from compost, leading to oxygen depletion in soil aggregates and the creation of anaerobic microsites that contribute to denitrification (Philippot *et al*., 2011). Vertisols, in particular, have a shrink-swell clay matrix that is especially susceptible to the formation of such microsites due to high levels of moisture and organic matter, which inhibit gas diffusion and facilitate anaerobic conditions at moderate water potentials (Dalal *et al*., 2003). Such findings are also supported by Liu *et al*. (2024), who showed that the concomitant use of manure compost and urea led to significantly higher N_2O emissions compared with urea used in isolation, attributed to increased denitrification fueled by organic carbon provided by the compost.

One interesting trend identified in the current experiment was that N_2C_2 (496.78 kg N ha-^{1}) had much lower N_2O emissions than N_2C_1, despite receiving a greater compost load. This negative correlation between the compost rate and N_2O emissions at the maximum N level indicates that increased organic input might have facilitated increased microbial N immobilization, thereby reducing the inorganic N reserves available for denitrification (Geisseler & Horwath, 2009). This is consistent with other researchers who found that mixing green waste compost with feedlot manure decreased the concentration of mineral N in soils and, as a result, inhibited N_2O emissions by over 50% compared with manure applied alone (Dalal *et al.,* 2009). Also, elevated compost inputs have altered the structure of the microbial community in soil, shifting the equilibrium between N_2O-producing and N_2O-consuming microbial communities, thereby promoting the reduction of N_2O to N_2 and increasing microbial activity under high organic matter conditions (He *et al*., 2024; Li *et al.,* 2024). Chen *et al.* (2025) also recognized that partial N fertilizer replacement with compost decreased cumulative N_2O emission rates by 53 %, indicating that at sufficiently high rates of compost, the denitrification-promoting impact of inorganic N addition could be partially counteracted by the N immobilization capacity of organic amendments.

This was evident by the rapid decline in Potentially Mineralizable Nitrogen (PMN) seen at the higher C and N application rates (Table 3). A great increase in labile carbon can stimulate heterotrophic microbial activity (Butterbach-Bahl *et al*., 2013).

In connection with the N_2O emission patterns in this study, the maximum mineralizable N (224.9 kg ha^{-1}) was recorded in the N_2C_1 treatment during the first seven days succeeding fertilizer application, suggestive of a fast release of available N from organic and inorganic sources (Figure 5, Table 3). The lowermost mineralizable N (20.8 kg ha^{-1}) in the N_0C_0 treatment further emphasized the important contribution of additional N inputs to soil N availability. Yet, the reduction in N_2O emissions and mineralizable N together in the C_2 treatments at similar N levels (N_1C_2 and N_2C_2) indicates that higher compost rates could induce N immobilisation or alter microbial community functions, as observed by Chen *et al.* (2013) and Geisseler & Horwath (2009).

After applying water on day 28 to reach 60% WFPS, daily N_2O emissions declined by 27% -45% across all treatments (Figure 1). This reduction likely reflects fluctuations in oxygen availability and microbial respiration patterns. The decline in N_2O emanations after water application on day 28 is due to the concealment of the nitrification process under anaerobic conditions created inside the cores after increasing WFPS over 60%. Under these anaerobic conditions, advanced denitrification (>80% of WFPS) minimised N_2O generation by limiting O_2 availability (Davidson *et al.,* 2014).

The decrease in daily mineralizable N from day 7 to 28 across all treatments indicates a temporal reduction in labile N forms, likely due to microbial uptake and reduced substrate availability (Figure 5). These sequential dynamics highlight the significance of synchronising N release with crop demand to reduce environmental losses and boost nutrient use efficiency (Congreves *et al.,* 2015).

Soil mineral N availability, predominantly NH_4^+ and NO_3^-, followed projected trends based on N input levels. Soon after adding compost and ammonium sulfate, NH_4^+ concentrations amplified across all treatments, presenting the highest value (179.4 kg N ha^{-1}) in N_2C_2 at day 7 (Figure 3). Though NH_4^+ declined drastically to close to 20 kg N ha^{-1} by day 28, reflecting nitrification, quick microbial uptake, or immobilization (Chen *et al*., 2013).

Nitrate concentrations improved frequently throughout the first 28 days in all treatments (Figure 4), maximizing at 137.9 kg NO_3^--N ha^{-1} in N_2C_1. On day 28 after water application (saturation), NO_3^- levels dropped rapidly, suggesting increased leaching/ denitrification losses. The sequential NO_3^- dynamics demonstrate the significance of synchronizing N availability with plant N uptake to avoid gaseous losses to the environment (Congreves *et al*., 2015).

The results of this study have implications for the long-term application of compost to cropping fields, with recurrent compost applications potentially immobilising excess N and decreasing N_2O emissions via the accumulation of soil carbon. However, if repeated compost additions aren't combined with reduced N rates, the potential for N_2O production remains high. In contrast, the lowermost daily emissions (17 g N ha^{-1}) were witnessed in the control (C_0N_0), which is unfertilized and unamended, emphasising the significant role of both organic and inorganic N inputs in N_2O production (Table 2).

Effects of compost and Nitrogen fertilizer rates on cumulative CO_2 emissions

Soil CO_2 emissions representing microbial respiration have responded strongly to compost and N additions. A statistically significant increase ($p < 0.05$) in CO_2 emissions across all compost-amended treatments (compared to the control) further confirms that compost is a strong stimulator of soil microbial activity and carbon turnover (Lal, 2004). Aligning with the results of former research, compost application enhanced soil CO_2 emissions, owing to the supply of labile C (de Urzedo *et al*., 2013; Nguyen *et al*., 2014; Liyanage *et al*., 2019).

N fertilizer (C_0 treatments) did not significantly affect cumulative CO_2 emissions (N_0C_0: 3.7 Mg C ha $^{-1}$; N_1C_0: 9.8 Mg C ha $^{-1}$; N_2C_0: 7.4 Mg C ha ^{1}), and all three treatments were essentially the same ($p > 0.05$). This tendency implies that the direct impact of additions of inorganic N in the absence of OA on the soil's heterotrophic respiration in the short-run incubation routine of the current study was insignificant. This is consistent with the fact that CO_2 emissions into the atmosphere from mineral fertilizer-amended soils are primarily limited by the presence or absence of decomposable organic carbon, rather than by N supply (Wang *et al.,* 2023). The small CO_2 response to N fertilizer can also be explained by the low native soil organic carbon content of the Vertisol, which limited the amount of mineralizable substrate available to the microbial community.

Conversely, cumulative CO_2 emission in all N fertilizer treatment levels was greatly triggered by the compost application, which was evidently dose-dependent in most treatments. Treatments with compost had significantly higher CO_2 emission than their corresponding unamended treatments, which was due to increased microbial heterotrophic respiration fuelled by the mineralisation of labile organic carbon provided by the compost. The result is also in line with the existing and well-reported stimulatory effect of compost additions on soil microbial activity and CO_2 emissions, since when labile organic carbon additions through compost are high, microbial activity and CO_2 release have the potential to rise significantly (Liang *et al*., 2017). Similar results were found by Wang *et al*. (2023), who also showed that the combined use of organic and inorganic fertilizers greatly increased the rates of soil respiration as compared to the use of only inorganic fertilizer, which was explained by improved content of soil organic matter and activity of microbial biomass. Moreover, Chau *et al*. (2023) claimed that applying compost to agricultural soils significantly increased CO_2 emissions, and the magnitude of these emissions was closely associated with the lability of the applied organic carbon and its decomposability.

In the current study, the highest cumulative CO_2 emission was observed in the N_1C_2 treatment (69.5 ± 13.4 Mg C ha^{-1}), which was significantly higher than in any other treatment ($p < 0.05$). This finding indicates that a middle range N rate with maximum compost input provided the most favorable conditions where activity of microbial decomposers occurred, perhaps by activating a priming effect in which new organic matter inputs catalyzed the degradation of both new and already existing soil organic carbon in the soil by increasing the turnover of microbial biomass (Kuzyakov *et al.,* 2000). The priming effect of stimulating organic and inorganic N co-applications to produce CO_2 has been demonstrated in several studies, and the addition of N has been shown to suppress the intensity of the priming response in changing microbial metabolic strategies and community structure (Zheng *et al*., 2023; Rocci *et al.,* 2024).

An especially remarkable finding was that N_2C_1 (17.8 ± 5.8 Mg C ha^{-1}) produced the same CO_2 emissions as the no-compost treatments, despite being fed compost at a moderate rate. This indirect inhibition of CO_2 emissions at high N rates and moderate compost levels can be explained by nitrogen's tendency to inhibit microbial decomposition activity. Inorganic N in high concentrations has also been reported to inhibit microbial heterotrophic respiration in various ways, such as the down-regulation of the ligninolytic enzyme expression, osmotic stress on the microbial cell, and alteration of the microbial community stoichiometry, which diminishes the effectiveness of organic matter breakdown (Yeung *et al*., 2025; Zheng *et al*., 2023). In particular, it has been proven that excess nitrogen inhibits the breakdown of substrates that contain lignin especially those that are enriched with particulate organic carbon (Yeung *et al*., 2025). Besides, elevated levels of nitrogen may elevate osmotic potential and lower soil PH, inhibiting microbial biomass and enzyme activity Springer (Zheng *et al.,* 2023). This inhibited emission of CO_2 by nitrogen is also supported by Jian *et al.* (2023), who noted that with increasing application rates of nitrogen, soil decomposition of soil organic matter and plant residues in planted soils is inhibited, especially at high rates. All these findings indicate that the N fertilizer, compost and CO_2 emission relationship is non-linear and very susceptible to carbon and the nitrogen stoichiometric ratio.

Motives to reduce CO_2 under submerged conditions after 28 days

The measured CO_2 emission decreased after 28 days of soil saturation, which can be explained by a number of interconnected biogeochemical processes that were related to the progressive transition of anaerobic environments within the submerged soil profile. In the long-term waterlogged environment, the diffusive uptake of atmospheric oxygen (O_2) into the soil is severely limited by its very low diffusion coefficient into water - about 10000 times lower than in air - and results in the rapid disappearance of O_2 in the soil matrix and a resultant inhibition of the aerobic heterotrophic microbial respiration, the most common biological process that produces CO_2 by oxidizing soil organic matter (Akter *et al*., 2024). Flooding conditions generally inhibit the overall mineralization of soil organic carbon because it is in the absence of O_2 needed to make the oxidative-based enzyme reaction, which leads to reduced CO_2 release to the soil (Miller *et al*., 2001).

Combined implications

The results of the current research highlight the intricacy of GHG emission processes in Vertisol soils exposed to organic and inorganic N sources. The use of compost is strongly promoted as a method for enhancing soil fertility and carbon sequestration (Wong *et al*., 2023; Liu *et al*., 2024). The current findings reveal that simultaneous use of compost with inorganic N fertilizers can greatly increase N_2O and CO_2 emissions, especially in the intermediate compost and high N levels. The strong N_2O emission in the N_1C_1 and N_2C_1 treatments has serious implications on the global warming potential of the two combinations since N_2O has a global warming potential of about 273 times higher than CO_2 on a 100-year time scale (IPCC, 2021). These results suggest that compost and inorganic N application rates should be optimized in subtropical cropping systems to balance the agronomic advantages of combining organic-inorganic nutrient management with the necessity to reduce GHG emissions (He *et al.,* 2024; Chen *et al.,* 2025).

These results mutually propose that compost addition affects microbial-mediated processes differently, depending on the compost and N fertilizer rates. Altogether, the findings exhibit complex and dynamic interactions among fertilizer N, compost, and soil microbial processes. Moderate compost rates enhance both CO_2 and N_2O emissions due to improved microbial activity, nitrogen mineralization, and substrate availability. In contrast, higher compost rates appear to mitigate N_2O emissions while stimulating CO_2 release, likely due to transfers in microbial pathways, redox conditions, or nutrient stoichiometry.

Soil NH_4^+ and NO_3^- dynamics reflected fast transformations of applied N rates. This fast transformation pointed out the transient nature of available mineral N underneath microbial control. The water application to the soil played a significant role in regulating emissions of both CO_2 and N_2O and nutrient retention, representing the importance of water addition in shaping soil biochemical reactions.

Commonly, these results describe the complex interactions between compost and N fertilization rates in controlling soil N conversions and gaseous N losses. Adding moderate compost rates might enhance N mineralisation and release higher N_2O fluxes; however, higher compost rates could mitigate fluxes, potentially via microbial or physicochemical mechanisms that require further exploration. The outcomes on compost and N application rates highlight the significance of not only confirming adequate nutrient supply but also considering environmental dynamics; for example, soil moisture control as a fragment of nutrient planning. This might help diminish gaseous N losses and restore soil health and efficiency.

CONCLUSIONS

The paper offers new information on short-term interactive impacts of urban-compost and inorganic nitrogen (N) fertilizer rates on N_2O and CO_2 emissions of a subtropical Vertisol soil under controlled incubation conditions. The overall results show that inorganic N fertilizer used as a biofilm had no statistically significant influence on cumulative N_2O emissions, which proves the hypothesis that the availability of labile carbon substrates is the key constraining factor that would influence the activity of denitrification in this type of soil. However, when compost was used simultaneously with inorganic N fertilizer, the emissions of N_2O were significantly increased. The maximum response was observed at the middle rate of compost and high rate of inorganic N fertilizer (N_2C_1: 1031.96 ± 124.00 kg N ha $^{-1}$), which showed that the relationships between organic carbon and inorganic N fertilizers were critical in the induction of microbial denitrification in the heavy clay matrix of Vertisol soils. In terms of CO_2 emission, the application of compost was observed to be the primary cause of the higher heterotrophic respiration of soil which showed a general dose-dependent relationship to compost levels regardless of the rate of fertilization with N. This cumulative CO_2 emission at the highest level (69.5 ± 13.4 Mg C ha^{-1}) is explained by the stimulation of microbial degradation activity and the priming of native soil organic matter mineralisation through laboratory organic carbon compost. On the other hand, the sudden inhibition of CO_2-evolution in the N_2C_1 treatment implies that high inorganic N levels could prevent microbial degradation of organic nutrients by nitrogen-mediated down-regulation of ligninolytic enzyme action and changes in microbial composition stoichiometry, which is of significance to the management of combined organic and inorganic nutrient feeds in subtropical cropping systems. Finally, the findings of this research indicated that although using composts complemented with inorganic N fertilizer, has agronomic advantages in terms of soil fertilization, composts also have a high potential of increasing GHG emissions, especially N_2O, of Vertisol soils. According to the product of the global warming potential of N_2O, which is 273 times higher than that of CO_2 on a 100-year time-span (IPCC, 2021), it can be inferred that the notable levels of N_2O emissions under organic-inorganic N management draw a significant environmental trade-off to the design of fertilization options in subtropical agriculture. In a practical perspective, the application of compost at rates that optimise agronomic benefit and do not cause a disproportionate response in N_2O emissions - presumably below the C_1 level when in combination with high inorganic N rates - is the most environmentally sound management practice to Vertisol soils in subtropical cropping systems. Moreover, it was noted that higher compost rates (C_2) partly inhibited the N_2O emissions in comparison with medium rates (C_1) at the same level of N fertilizers, which indicated that high levels of organic inputs might encourage more microbial N immobilization and activate a microbial population to reduce N_2O, and this needs to be further investigated under field conditions and over a longer period. The future study should be devoted to the investigation of long-term impacts of mixed application of compost and inorganic N fertilizers on the decrease in GHG emissions, soil carbon sequestration, and crop yield under field conditions in subtropical Australia, because the study incubation period used in the current study might not counter all the seasonal changes in soil moisture, temperature, and biological activity in the field. Also, mechanistic information on how the soil microbial communities, specifically abundance and activity of nitrifying, denitrifying and N_2O -reducing microbial communities, would respond to varying combinations of compost and N fertilizers would be generated through the molecular characterisation of the soil microbial communities.

AUTHOR CONTRIBUTION

The author contributed to conceptualization, methodology, investigation, data collection, manuscript preparation, review, and final editing of the manuscript.

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