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Transforming waste to wealth: Impact of food waste-derived soil amendments and synthetic nitrogen fertilizer on soil dynamics

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Abstract

Approximately one-third of all food produced globally goes to waste, highlighting the need for sustainable waste management technologies like composting and anaerobic digestion. These technologies convert food waste into soil amendment products such as compost, liquid digestate (LD) and solid digestate (SD). However, these food waste-derived soil amendments have relatively low nutrient contents compared with synthetic nitrogen (N) fertilizers such as urea, making their agricultural use challenging. Despite this, food waste-derived soil amendments can enhance the physical and biological properties of soil, potentially creating synergistic effects when combined with synthetic N fertilizers. This study aimed to investigate effects of food waste-derived amendments in soil applied at 50 kg ha^{-1} total N (compost, LD or SD) and synthetic N fertilizer [urea ammonium nitrate (UAN)] at 50 and 100 kg ha^{-1} total N. Over 56 days of soil incubation, greenhouse gases (CO_2, N_2O), soil chemistry (NH_4^+–N, NO_3^-–N, pH) and microbial biomass C (MBC) were measured. Results showed that LD + UAN 50 reduced cumulative N_2O emissions by 23% compared with UAN 100, despite having the same total N and similar available N rate applied to soil. Replacing UAN with LD in farming practices can supply equivalent available N while lowering N_2O emissions, offering a sustainable nutrient strategy. Moreover, applying food waste-derived soil amendments can enhance N retention in soils, reducing the need for increased applications of synthetic N fertilizers to compensate for N deficits in farming. Food waste-derived soil amendments can also act as a slower N release compared with UAN, reducing nitrogen run-off. SD had the highest CO_2 emissions, followed by LD and compost. SD + UAN 50 increased MBC levels because of higher carbon content and labile carbon, and available N because of the application of UAN. The major drawback of using SD compared with LD is that the process of evaporating LD to form SD causes high ammonia volatilization (ammonium in solution into ammonia gas) rates, reducing the available N in SD. Therefore, future studies should explore strategies to reduce ammonia volatilization of LD.

KEYWORDS
ammonia volatilization, compost, digestate, GHG, nitrification

1 | INTRODUCTION

Globally, the standard food waste disposal practices of landfilling and incineration have caused widespread pollution of greenhouse gas (GHG) emissions (~20% of total global emissions), decreased land-use area and contaminated groundwater because of landfill leachate (FAO, 2011; O'Connor et al., 2021). Furthermore, improper agricultural practices, climate change and soil contamination are degrading soils, reducing soil organic matter and jeopardizing soil health (Ferreira et al., 2022). Additionally, production costs of synthetic fertilizers, particularly mineral N fertilizers, have recently increased because of the scarcity of fossil fuels, a major resource in manufacturing (Nayak-Luke et al., 2022).

To address these issues, the conversion of food waste into a biofertilizer to reach a circular bioeconomy is a current strategy to reduce the production of synthetic fertilizers by non-renewable methods. Composting and anaerobic digestion can recycle nutrients back into the soil, improving soil fertility. Food waste-derived soil amendments can enhance soil health by increasing organic matter, improving soil structure and boosting microbial activity (O'Connor et al., 2021). A circular bioeconomy can be defined as the renewable conversion of waste from various industries and waste streams into value-added products such as biofuels, bio-based materials, nutrients and food (Stegmann et al., 2020). Various non-governmental organizations have legislated goals and strategies to help close the circular bioeconomy loop. For instance, the United Nations has set a Sustainable Development Goal Target (SDG Target 12.3) to reduce food waste by 50% by 2030, with half of the world's countries setting specific targets to achieve SDG 12.3 (United Nations, 2021). Converting food waste into a nutrient source and soil amendment is an effective strategy to achieve this goal. Thus, recovering food waste-derived nutrients for soil application offers a sustainable method of waste management that can increase soil organic matter and prevent soil degradation on traditional agricultural farms (Leogrande & Vitti, 2019; Oyetunji et al., 2022; Yang et al., 2020). Moreover, studies suggest that composts and digestate are potentially viable for carbon sequestration (Béghin-Tanneau et al., 2019; Smith et al., 2014). For example, Béghin-Tanneau et al. (2019) recorded that digested maize silage sequestered 63% of exogenous organic matter, which has an amending effect, over a period of 178 days. However, carbon sequestration of food waste-derived soil amendments remains limited, and more research is required (O'Connor, Mickan, et al., 2022).

Food waste composting and anaerobic digestion from domestic and commercial sectors are the most common food waste management strategies, producing biofertilizers as the main product (e.g. compost) or as a by-product (e.g. digestate) that requires careful management (O'Connor et al., 2021). Food organic and garden organic (FOGO) recycling to compost is a growing waste management practice legislated by local state governments as a means of waste diversion in many countries (Department of Water and Environmental Regulation, 2020). Liquid digestate (LD) derived from food waste is typically wasted or applied to soils and potting mixes. LD is commonly composted prior to soil application. Solid digestate (SD) is an attractive option for anaerobic digestion facilities because of the high costs and persistent bottlenecks associated with the transportation, post-treatment and storage of LD (Jin et al., 2021; Sheets et al., 2015). Exploring the value of SD as a partial replacement for mineral N fertilizer is needed to determine the overall techno-economic assessment of dewatering LD. Given these benefits, this study aims to compare the effects of food waste-derived soil amendments and synthetic fertilizers on soil carbon and nitrogen dynamics to assess their potential for sustainable agriculture. Despite the effectiveness of compost, LD and SD as nutrient sources and soil conditioners, the impact of these food waste-derived soil amendments, both when used alone and in synergy with synthetic fertilizers, on soil function remains unclear. Studies have shown that adding biofertilizers to soil can increase the abundance of plant-growth-promoting microbes and compounds that significantly impact nutrient dynamics (Cheong et al., 2020; Scaglia et al., 2017). However, little is known about the relative leaching of nitrate and nitrous oxide emissions of compost and digestates in soils compared with mineral

N fertilizers such as urea ammonium nitrate (UAN) (O'Connor, Mickan, et al., 2022). Moreover, the study can demonstrate how application of synthetic fertilizers with food waste-derived soil amendments may offer effective fertilizer management strategies to farmers (Nayak-Luke et al., 2022).

Therefore, this study compares the C and N dynamics of compost, LD and SD with a regularly used N fertilizer (UAN) to investigate their potential widespread use within agriculture. Moreover, the study compares the agronomic values between LD and SD. The specific objectives were to: (i) compare the effect of three food waste-derived soil amendments (FOGO compost, LD and SD) on various soil properties and GHG emissions, (ii) quantify the effect of inorganic nutrient input (UAN) on soil C and N cycling processes combined with food waste-derived soil amendments and (iii) evaluate both LD and solid digestate SD as fertilizers, as well as their impact when applied to soils, focusing on their impact on nitrification. We hypothesize that (i) the application of food waste-derived soil amendments to a low fertile, moderately acidic, sandy loamy soil will enhance soils characteristics (pH, microbial biomass C and N, total C and N, plant-available nutrients, soil respiration), but elevate electrical conductivity; (ii) combination of food waste amendment and inorganic fertilizer will enhance soil C cycling and respiration; and (iii) the evaporation of raw digestate to produce SD will alter the fertilizer value and impact nitrification in soils.

2 | MATERIALS AND METHODS

2.1 | Collection of food waste compost, digestate, liquid urea ammonium nitrate and soil

Compost and food waste digestate were collected from a composting and anaerobic digestion facility at Jandakot, Western Australia, that distributes Australian Standard 4454 composts, soil conditioners, mulches and potting mixes to gardening outlets within Australia (Richgro®, 2022). Compost was derived from domestic and commercial food and garden organic waste. The digestion facility utilizes mesophilic anaerobic digestion processes and is identical to the study by Bühlmann et al. (2021). LD was derived from commercial food waste, including expired food from grocery stores, organic waste from food processing facilities and liquid wastes such as milk and brewery waste. SD was obtained by evaporating LD at 60°C in an oven yielding of 2.5% w/w in 72 h. The compost and food waste digestate were sieved (<2 mm). Liquid urea ammonium nitrate (Flexi-N) was collected from the chemicals company CSBP® and comprised 7.7% w/w nitrate, 7.7% w/w ammonium and 16.6% urea (32.0% total nitrogen content).

The soil was collected from the UWA farm Ridgefield 25 km northwest of Pingelly, Western Australia (32°28′44.1″S, 116°59′56.2″E), which has a Mediterranean-type climate with wet, cool winters and dry, hot summers. We collected topsoil down to 10 cm. The sandy loamy soil is characterized as a Eutrophic Kurosol (according to Australian soil classification; Isbell, 1996).

2.2 | Experimental design

The measured carbon and nitrogen parameters included nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions, soil ammonium (NH_4^+) and nitrate (NO_3^-), and microbial biomass carbon (MBC). CO_2 emissions were measured as an index of microbial respiration. The application rate of treatments in the study was 0 (control), 50 and 100 kg ha^{-1} total N input (Table S1). Food waste-derived soil amendments were applied to the soil at 50 kg ha^{-1} total N, and UAN was added to the soil at 50 kg ha^{-1} total N. 50 kg ha^{-1} total N is a typical application rate given to grasses in agriculture (Pereira et al., 2022; Ren et al., 2020). Moreover, this specific application rate was used to support subsequent plant growth experiment by O'Connor et al. (2024). Food waste amendment + UAN treatments were added to soil at a rate of 100 kg ha^{-1} total N (food waste amendment was added at 50 kg ha^{-1} total N and UAN was added at 50 kg ha^{-1} total N). A positive control of UAN (100 kg ha^{-1} total N) was included to compare food waste-derived soil amendments + UAN. The experimental design had nine treatments with four replicates at different rates: control (0 kg ha^{-1} N), UAN 50, UAN 100 (positive control), compost, compost + UAN 50, liquid digestate (LD), LD + UAN 50, solid digestate (SD) and SD + UAN 50, where UAN 50 is urea ammonium nitrate applied at 50 kg ha^{-1} N and UAN 100 is urea ammonium nitrate applied at 100 kg ha^{-1} N (see Table S1). Food waste-derived soil amendments and water (9.58 mL water per 50 g soil, equivalent to 45% water holding capacity of soil) were added to 50 g soil and placed into 120-mL screw-cap tubes. The water content was consistent among treatments and less water was added to LD treatments, accounting for the high volume of water in LD. The tubes were thoroughly mixed by shaking and then were sealed with Parafilm® to allow for gas exchange and to avoid water evaporation loss. Samples were incubated at 25°C in a temperature control room over 56 days with a time series of 0, 0.5, 1, 3, 7, 14, 28 and 56 days. This time series is consistent with other incubation studies (Jenkins et al., 2023; Shayesteh et al., 2023) and captures the immediate and prolonged effects of treatments in soil. Water was added every 3 days to each sample to account for any evaporation loss. Samples were destructively harvested for each time series to reduce cross-contamination among each time-series. Therefore, 288 samples were harvested throughout the experiment (9 treatments ×4 replications ×8 time series).

2.3 | Soil gas emissions (CO_2 and N_2O)

CO_2 and N_2O emissions were analysed using the closed jar method (Barton et al., 2013). Each 120-mL screw-cap tube samples were placed into airtight 523-mL mason jars fitted with a septum and left in a 25°C control temperature room; measurements were taken after 2 h by extracting 20 mL headspace gas from the jar using a 20-mL syringe and injecting it into a 12-mL pre-evacuated gas vial. Gas chromatography was used to measure CO_2 and N_2O using an Agilent 7890a GC (Agilent Technologies Inc, Santa Clara, CA, USA).

A first-order kinetic model, described by Song et al. (2021), was fitted to the cumulative CO_2 and N_2O data to evaluate CO_2 and N_2O emission dynamics during the incubation period. The model accounts for the rapid and subsequent slow release of gas observed in soil, using the following equation:

$$C = C_r \cdot \left(1 - \exp\left(-K_r t\right)\right) + C_s \cdot \left(1 - \exp\left(-K_s t\right)\right) \quad (1)$$

where C is cumulative CO_2 or N_2O emitted (CO_2 g soil^{-1} day^{-1}) at time (t), and C_r and C_s are the rapid and slow release of C or N from soil at specific rates of K_r and K_s.

2.4 | Analysis of soil properties

Soil pH and EC were measured in a 1:5 w/w air-dried soil: DI-water solution using a Thermo Scientific Orion Versa Star Pro Benchtop pH Meter (Thermo Fisher Scientific Inc., Waltham, MA, USA). Soil NH_4^+ and NO_3^- were measured according to Searle (1984) and Keeney and Nelson (1983) using a 1:4 w/w soil: 0.5 M K_2SO_4 ratio. Samples were filtered using a 0.45-μm syringe filter and were subsequently analysed using a Lachat QuikChem 8500 Series 2 flow injection system (Lachat instruments, Loveland, CO, USA). MBC was determined by measuring dissolved organic carbon (DOC) using the chloroform fumigation extraction method (Wu et al., 1990). DOC was measured in fumigated and non-fumigated soil was by adding 40 mL 0.5 M K_2SO_4 to 10 g soil (1:4 soil: extract, w/w) in 50-mL glass beakers with boiling chips. Fumigated beakers were placed in a vacuum desiccator with 30 mL chloroform for 24 h in darkness. The DOC extract was measured using an OI Analytical Aurora 1030 Wet Oxidation TOC Analyzer (College Station, TX, USA). The difference in DOC between fumigated and non-fumigated samples represented chloroform-labile carbon, equivalent to for MBC (mg kg^{-1}):

$$\mathrm{MBC} = E_c / K_c \quad (2)$$

where E_c is DOC fumigated sample (mg kg^{-1}) – DOC non-fumigated sample (mg kg^{-1}) and $K_c = 0.45$, a constant value representing the DOC extraction efficiency (Jenkinson, 1981).

2.5 | Statistical analysis

The effects of food waste amendment and UAN on nitrogen parameters and soil properties were determined by a two-way analysis of variance (ANOVA). A one-way ANOVA and Tukey's HSD were used to compare significant treatment effects. Pearson's correlation was used to quantify the relationships between soil parameters. A principal component analysis (PCA) was used to quantify the relationship between the treatment and measured parameters over time. Standard errors were added to all graphs to express variation. Standard deviations were used in tables. All statistical analysis was performed using the programming language of R (Ihaka & Gentleman, 1996).

3 | RESULTS AND DISCUSSION

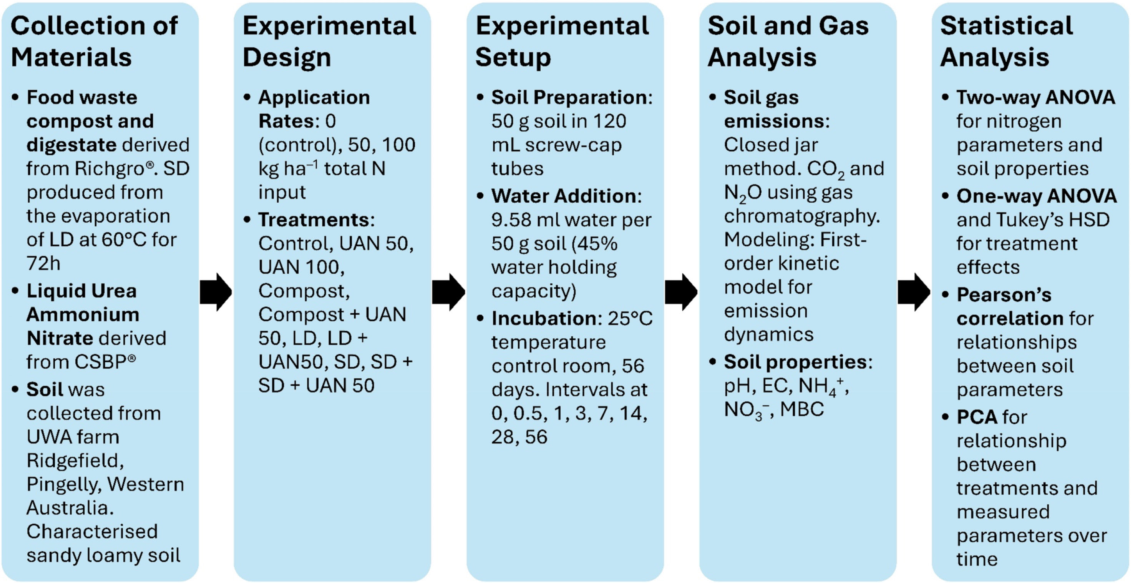
3.1 | Soil chemical properties

Table 1 shows that the soil pH was slightly acidic at pH 5.9. The UAN, compost, LD and SD were neutral to alkaline at pH 7, 7.51, 7.97 and 9.00, respectively. The slightly alkaline values of digestate are because of their high NH_4^+ contents, consistent with Logan and Visvanathan (2019). Figure 1 shows the evolution of pH and EC in soil. The initial application (Day 0) of treatments significantly increased pH because of their alkaline nature ($p < .05$) (Table 1, Table S2). However, across the 56 days, pH decreased in all treatments (Figure 2). The observed decrease in soil pH can be attributed to the nitrification process, where ammonium (NH_4^+) is oxidized to nitrate (NO_3^-), releasing hydrogen ions (H^+) into the soil (Bolan et al., 1991). This process is catalysed by nitrifying bacteria such as Nitrosomonas and Nitrobacter, which convert NH_4^+ first to nitrite (NO_2^-) and then to NO_3^- (Bolan et al., 1991). The release of H^+ ions during these reactions results in a net acidification of the

TABLE 1 Characteristics of soil and food waste fertilizer products.

Parameter	Soil	UAN	Compost	Liquid digestate	Solid digestate
Total C (%)	7.04	0	15.28	3.5	36.93
Total N (%)	0.36	32	1.33	0.39	5.13
Total P (%)	–	0	0.21	0.04	1.70
Total K (%)	0.02	0	0.47	0.14	5.06
Ammonium–N (mg kg^{-1})	2	77,000	8	2300	157
Nitrate–N (mg kg^{-1})	5	77,000	580	33	3
Available-P (mg kg^{-1})	45	0	24	0.01	741
Na (%)	–	0	0.20	0.17	3.76
S (mg kg^{-1})	20.3	0	0.18	0.01	0.75
EC (mS cm^{-1})	0.098	–	2.98	27.52	15.74
pH ($CaCl_2$)	4.8	–	7.30	7.92	8.28
pH (H_2O)	5.9	6.5–7.5	7.51	7.97	9.00

Abbreviation: UAN, Urea ammonium nitrate.



Collection of Materials

- **Food waste compost and digestate** derived from Richgro®. SD produced from the evaporation of LD at 60°C for 72h
- **Liquid Urea Ammonium Nitrate** derived from CSBP®
- **Soil** was collected from UWA farm Ridgefield, Pingelly, Western Australia. Characterised sandy loamy soil

Experimental Design

- **Application Rates**: 0 (control), 50, 100 kg ha^{-1} total N input
- **Treatments**: Control, UAN 50, UAN 100, Compost, Compost + UAN 50, LD, LD + UAN50, SD, SD + SD + UAN 50

Experimental Setup

- **Soil Preparation**: 50 g soil in 120 mL screw-cap tubes
- **Water Addition**: 9.58 ml water per 50 g soil (45% water holding capacity)
- **Incubation**: 25°C temperature control room, 56 days. Intervals at 0, 0.5, 1, 3, 7, 14, 28, 56

Soil and Gas Analysis

- **Soil gas emissions**: Closed jar method. CO_2 and N_2O using gas chromatography. Modeling: First-order kinetic model for emission dynamics
- **Soil properties**: pH, EC, NH_4^+, NO_3^-, MBC

Statistical Analysis

- **Two-way ANOVA** for nitrogen parameters and soil properties
- **One-way ANOVA** and Tukey's HSD for treatment effects
- **Pearson's correlation** for relationships between soil parameters
- **PCA** for relationship between treatments and measured parameters over time

FIGURE 1 Methodology flowchart.

soil. This acidification highlights the dynamic nature of soil pH influenced by amendment addition combined with microbial activity. Compost had a low NH_4^+ level (Table 1) and nitrification rate; hence, pH did not significantly differ from the control over the 56 days.

Figure 2b shows that the food waste-derived soil amendments significantly increased salinity ($p < .05$). Notably, LD and SD produced considerably higher EC values than compost because of the increased NH_4^+ concentration in LD and increased Na^+ in SD (Table 1). During the 56 days, soil EC gradually increased in the food waste amendment treatments but sharply increased in the UAN and food waste-derived soil amendments + UAN treatments before levelling-off after 28 days (Figure 2b). The concentrations of soluble salts and nutrients can be measured indirectly through soil EC (Carmo et al., 2016). Increased nitrogen availability through ammonification (organic nitrogen to NH_4^+ to NO_3^-) may have increased soil EC during the incubation period. While the food waste-derived soil amendments and UAN inputs significantly increased soil EC, the highest concentration only reached 520 µS cm^{-1}, considerably lower than threshold values for typical crops (<2500 µS cm^{-1}) (Machado & Serralheiro, 2017).

3.2 | Nitrogen dynamics

Figure 3 shows the evolution of NH_4^+ and NO_3^- in soil. The LD application significantly increased NH_4^+ ($p < .05$). The LD and UAN treatments had considerably more

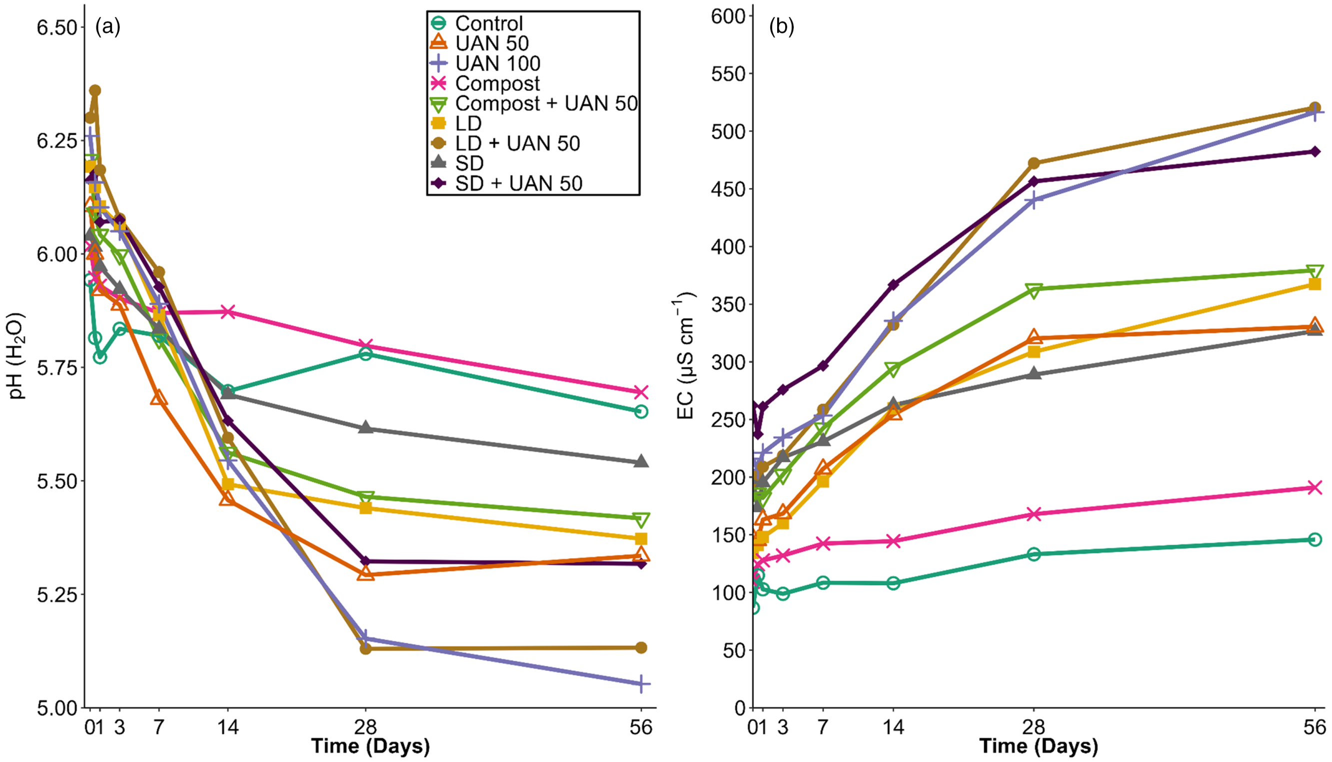


FIGURE 2 pH and electrical conductivity (EC) for nine treatments during 56 days of incubation. (a) pH (H_2O); (b) EC ($\mu S\ cm^{-1}$). LD, Liquid digestate; SD, Solid digestate; UAN, Urea ammonium nitrate. Points represent experimental data. Tables S3 and S4 show standard errors.

NH_4^+ than the SD and compost treatments. High levels of NH_4^+ in soil can enhance microbial activity and support plant growth. However, excessive NH_4^+ can lead to soil acidification and potential toxicity to plants if not properly managed. The conversion of NH_4^+ to NO_3^- via nitrification can mitigate these effects but also necessitates careful management to avoid nitrate leaching and associated groundwater contamination. There was no significant difference in NH_4^+ levels occurred between compost, SD and control (Table S5). The LD and UAN-amended soils had primarily plant-available nitrogen, whereas compost and SD had unavailable nitrogen (Table 1). The process of evaporating LD to SD at 60°C volatilized available NH_4^+, which was emitted as ammonia (NH_3) gas during dehydration (Li et al., 2016), with 99.99% of the NH_4^+ emitted in this study. If no volatilization occurred, the expected yield of NH_4^+ in SD would be 2300 mg kg^{-1} LD (Table 1); however, the actual yield was 2.58 mg kg^{-1}. Similarly, the expected yield of total N in SD would be 3900 mg kg^{-1} LD, but the actual yield was 1356 mg kg^{-1} LD. Therefore, the evaporation of LD resulted in a loss of 65.21% in total N, mainly because of ammonium volatilization.

New strategies to reduce NH_4^+ volatilization have recently improved its retention of NH_4^+ in SD (Li et al., 2016; Novak-Pintarič et al., 2020), such as adding of sulphuric acid. Sulphuric acid reduces the pH of liquid digestate and reacts with NH_4^+ in solution to produce ammonium sulphate (Novak-Pintarič et al., 2020). Therefore, it is crucial for future research to prepare acidified digestate and compare its properties and effects on soil with unacidified oven-dried SD.

During the 56-day incubation, soil NH_4^+ declined to 0 mg kg^{-1} in all treatments. Ammonification, resulting in the decomposition and mineralization of organic nitrogen, mostly occurred in the earlier stages of incubation. This observation aligns with Marzi et al. (2020), who reported similar results when organic amendments were applied to loamy sand soil. The low clay content in the soil likely contributed to the reduced ammonium fixation to clay particles, resulting in nitrification (Marzi et al., 2020). Nitrification of NH_4^+ to NO_3^- from nitrifying microorganisms likely increased NO_3^-, consistent with (Beeckman et al., 2018). Moreover, Figure 2 shows an inverse function as NH_4^+ converted into NO_3^-. However, some losses can result from NH_3 volatilization, especially with UAN application. Approximately one-quarter of urea is lost via NH_3 volatilization when broadcast on pasture at 100 kg ha^{-1} N (Bolan et al., 2004). However, the addition of organic amendments with a higher C:N ratio can mitigate the ammonia release from soil (Cao et al., 2022). Further investigation of ammonia release

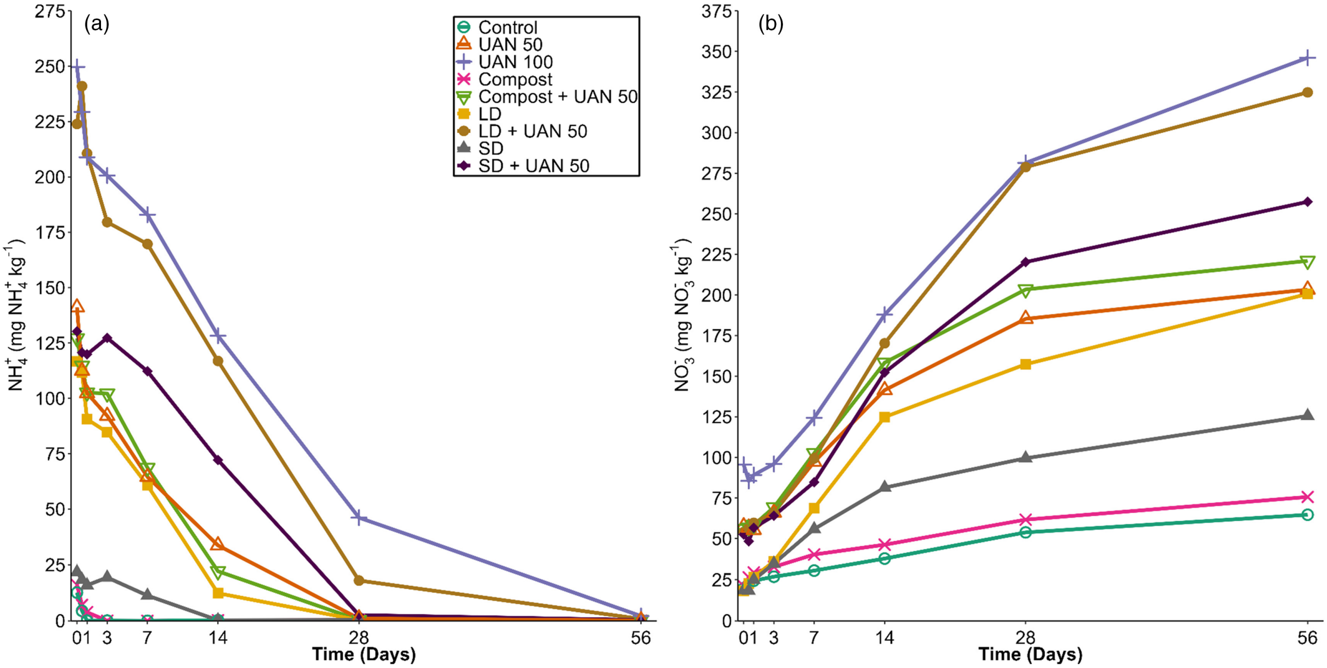


FIGURE 3 Mineralizable nitrogen evolution for nine treatments during 56 days of incubation. (a) NH_4^+ (mg NH_4^+ kg^{-1}); (b) NO_3^- (mg kg^{-1}). LD, Liquid digestate; SD, Solid digestate; UAN 50, Urea ammonium nitrate applied at 50 kg ha^{-1} total N; UAN 100, Urea ammonium nitrate applied at 100 ha^{-1} total N. Points represent experimental data. Tables S5 and S6 show standard errors.

of UAN compared with food waste-derived soil amendments is needed.

The food waste-derived soil amendments did not immediately elevate NO_3^- (Table S6), but UAN did. Over the 56 days, soil NO_3^- increased in all treatments (Figure 3). Table S10 shows that NO_3^- values significantly increased over time. Most notably, compost had nitrification rates comparable to the control by the end of the 56-day incubation. Compost also had no significant NO_3^- inputs when initially applied to the soil. Therefore, available N from compost immobilized in the soil at 50 kg ha^{-1} N over the 56-day incubation.

Applying the first-order kinetic model (Equation 1) revealed how food waste-derived soil amendments and UAN significantly increased soil N_2O emissions compared with the control, except for compost (Figure 4a; Table S7). The models in Figure 4 show that the curve fits well with R^2 values ranging from 0.990–0.999 (Table 2). N_2O emissions for compost did not significantly differ from the control (Table S7). The UAN 100 treatment had the highest N_2O emissions. SD had significantly lower N_2O emissions than LD. UAN-amended soils had greater N_2O emissions than organic-amended soils despite the same nitrogen application rate. LD had elevated N_2O emissions compared with compost and SD for treatments ± UAN. Microbial nitrification and denitrification processes in soils release N_2O emissions (Saggar et al., 2013; Thangarajan et al., 2013). Hence, UAN-amended soils with urea, ammonium and nitrate forms of N inputs increased NH_4^+ and NO_3^- levels, increasing nitrification and denitrification processes (see Figure 4). In comparison, food waste-derived soil amendments had reduced emissions as nitrogen is mainly in the form of organic nitrogen. The decrease in soil pH may have also inhibited N_2O reductase, increasing N_2O emissions (Liu et al., 2010). The treatments with the most available nitrogen (UAN 100 and LD + UAN 50) had the slowest N_2O production rate, as observed by the rapid- and slow-release rate (K_r and K_s values; Table 2) likely because of the prolonged nitrification of NH_4^+ (Figure 3a).

Nitrogen retention in agricultural systems is crucial for maintaining high plant yields. An effective agricultural system will apply N fertilizers that optimize the rate of plant-available nitrogen (NH_4^+ and NO_3^-) while reducing leaching and N_2O emissions (Anas et al., 2020). Compost and SD did not release as much available N into the soil as UAN and LD. LD had comparable NH_4^+ release into soil as UAN 50, which did not significantly differ during the 56-day incubation (Table S5). On Day 0, the NO_3^- release of LD into soil did not significantly differ from the control; however, on days 7 and 14, the NO_3^- levels significantly increased to levels comparable with UAN 50. Interestingly, LD + UAN 50 and UAN 100 produced similar results. The rapid increase in NO_3^- shows that LD had a higher nitrification rate than UAN. Overall, LD + UAN 50 had similar levels of available N to UAN 100 when applied at their respective rates to soil, but LD + UAN 50; had 23% lower N_2O emissions than UAN 100 over the incubation period. Moreover, Cao et al. (2022) also

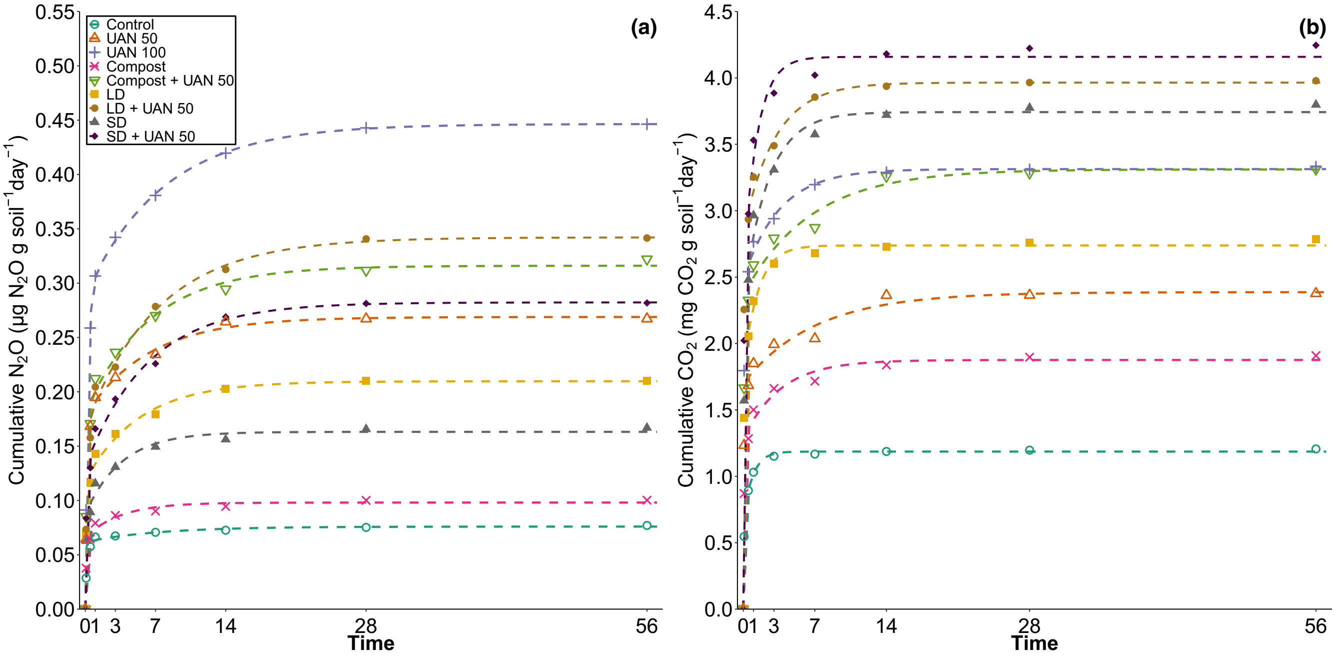


FIGURE 4 Gaseous emission first-order kinetic model for nine treatments during 56 days of incubation. (a) Cumulative N_2O (µg N_2O g soil^{-1} day^{-1}); (b) cumulative CO_2 (mg CO_2 g soil^{-1} day^{-1}). LD, Liquid digestate; SD, Solid digestate; UAN 50, Urea ammonium nitrate applied at 50 kg ha^{-1} total N; UAN 100, Urea ammonium nitrate applied at 100 kg ha^{-1} total N. Points represent experimental data, while dashed lines indicate the fitted model. Tables S7 and S8 show standard errors.

TABLE 2 Kinetic parameter treatment of nine treatments during 56 days of incubation.

	Kinetic parameters				
Treatment	C_r	C_s	K_r	K_s	R^2
Cumulative CO_2					
Control	0.68 ± 0.18	0.51 ± 0.17	16.84 ± 7.54	1.12 ± 0.54	.999
UAN 50	1.70 ± 0.16	0.69 ± 0.19	15.92 ± 5.57	0.14 ± 0.11	.993
UAN 100	2.49 ± 0.13	0.83 ± 0.14	15.67 ± 2.51	0.28 ± 0.13	.995
Compost	1.28 ± 0.20	0.59 ± 0.20	13.75 ± 5.99	0.28 ± 0.25	.999
Compost + UAN 50	2.36 ± 0.22	0.95 ± 0.25	15.01 ± 4.94	0.15 ± 0.12	.998
LD	1.80 ± 0.26	0.93 ± 0.25	18.41 ± 5.91	0.70 ± 0.36	.996
LD + UAN 50	2.84 ± 0.20	1.13 ± 0.20	19.19 ± 4.35	0.32 ± 0.15	.996
SD	2.33 ± 0.39	1.41 ± 0.39	13.19 ± 5.26	0.41 ± 0.27	.995
SD + UAN 50	2.55 ± 0.75	1.61 ± 0.73	17.64 ± 10.90	0.14 ± 0.11	.999
Cumulative N_2O					
Control	0.014 ± 0.0064	0.062 ± 0.0058	0.14 ± 0.18	7.31 ± 2.40	.995
UAN 50	0.090 ± 0.015	0.18 ± 0.014	0.158 ± 0.064	5.23 ± 1.30	.999
UAN 100	0.16 ± 0.015	0.29 ± 0.014	0.13 ± 0.030	4.29 ± 0.67	.999
Compost	0.032 ± 0.014	0.066 ± 0.0134	0.29 ± 0.32	10.11 ± 5.50	.990
Compost + UAN 50	0.13 ± 0.029	0.18 ± 0.027	0.16 ± 0.093	7.13 ± 3.59	.995
LD	0.091 ± 0.019	0.12 ± 0.018	0.19 ± 0.11	10.59 ± 4.96	.994
LD + UAN 50	0.17 ± 0.030	0.17 ± 0.027	0.14 ± 0.064	6.14 ± 3.46	.996
SD	0.076 ± 0.021	0.088 ± 0.020	0.28 ± 0.20	14.89 ± 10.06	.991
SD + UAN 50	0.15 ± 0.024	0.13 ± 0.021	0.16 ± 0.073	12.08 ± 6.56	.995

Note: Values represent mean with confidence interval values. C_r and C_s are the rapid and slow release of C or N from soil at specific rates of K_r and K_s. R^2 measures the goodness of fit of the kinetic model.

observed that the application of wheat straw slurry in soil resulted in a N_2O emission reduction of 40–46%, increasing nitrogen retention. The available N in compost did not significantly differ from the control, and SD had considerably less available N than UAN when applied at the same total N rate. However, these food waste-derived soil amendments are high in P and K (Table 1), offering great potential P and K inputs and act as a soil conditioner because of the high organic carbon. SD is more suitable as a fertilizer source than soil conditioner because of its high nutrient concentration.

The nitrogen cycle demonstrates that food waste-derived soil amendments provide a slow-release form of nitrogen in organic form with a high pH, which moderates the sudden nitrification and denitrification processes typically observed with UAN application. The mineralization of urea is also faster than humic nitrogen (found in the organic fraction of food waste-derived soil amendments) (Aranguren et al., 2021). Consequently, the use of food waste-derived soil amendments in slightly acidic soil results in decreased GHG emissions and improved nitrogen retention.

3.3 | Carbon dynamics

Food waste-derived soil amendments and UAN-amended soils significantly increased in microbial activity, evidenced by the large increase in CO_2 emissions within the first 14 days (Figure 4b; Table S8). After 14 days, most mineralizable carbon had been exhausted, as shown by the near-constant values. UAN increased the mineralization rate of food waste-derived soil amendments, as indicated by the increased release of CO_2 and available nitrogen (Figures 2 and 3). The decomposition of organic carbon from food waste-derived soil amendments provides a readily available energy source for soil microorganisms. This increased microbial activity is evidenced by higher CO_2 emissions, reflecting enhanced soil respiration. The presence of labile carbon fractions in liquid and solid digestates stimulates microbial growth, leading to higher microbial biomass carbon (MBC) levels, which are indicators of a healthy and active soil microbial community. All amendments had significantly higher soil respiration levels than the control (Table S8). After 56 days, SD had the highest cumulative CO_2 emissions, followed by LD and compost ($p < .001$). Compost had the lowest rate of soil respiration because of its highly stable C in complex forms being resistant to decomposition, and a higher C/N ratio than food waste digestate (O'Connor, Hoang, et al., 2022; Robertson & Groffman, 2015), as shown in Table 1. Compost and SD had the slowest rapid decomposition rate, evidenced by K_r values of 13.75 and 13.19 day^{-1}, respectively (Table 2) and likely because of their high C/N ratios and the low amount of labile carbon in compost (Song et al., 2021). Song et al. (2021) also reported that compost had a reduced rapid rate of decomposition compared with digestate. SD had higher cumulative CO_2 emissions than LD in our study because of the higher C inputs. Thus, the low C/N ratio of LD resulted in a more rapid decomposition, evidenced by high K_r and K_s values of 18.41 and 0.70 day^{-1}, respectively.

MBC reflects soil microbial activity and is a fraction of total carbon (C). It is crucial for nutrient cycling, soil formation and soil health, with higher MBC levels indicating higher microbial activity and healthier soils (Ren et al., 2019). Over the 56-day incubation period, SD + UAN 50 was the only treatment with a significantly

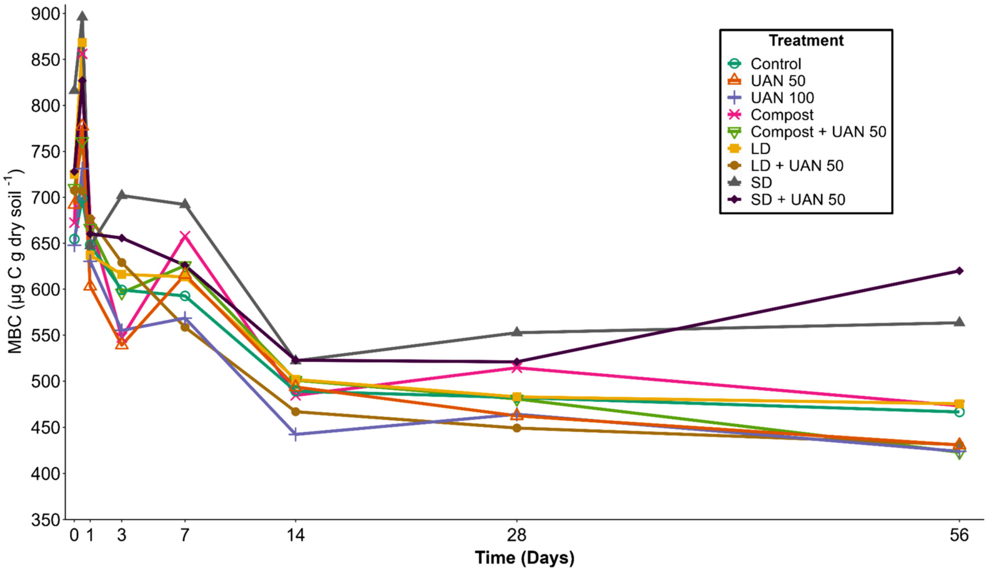


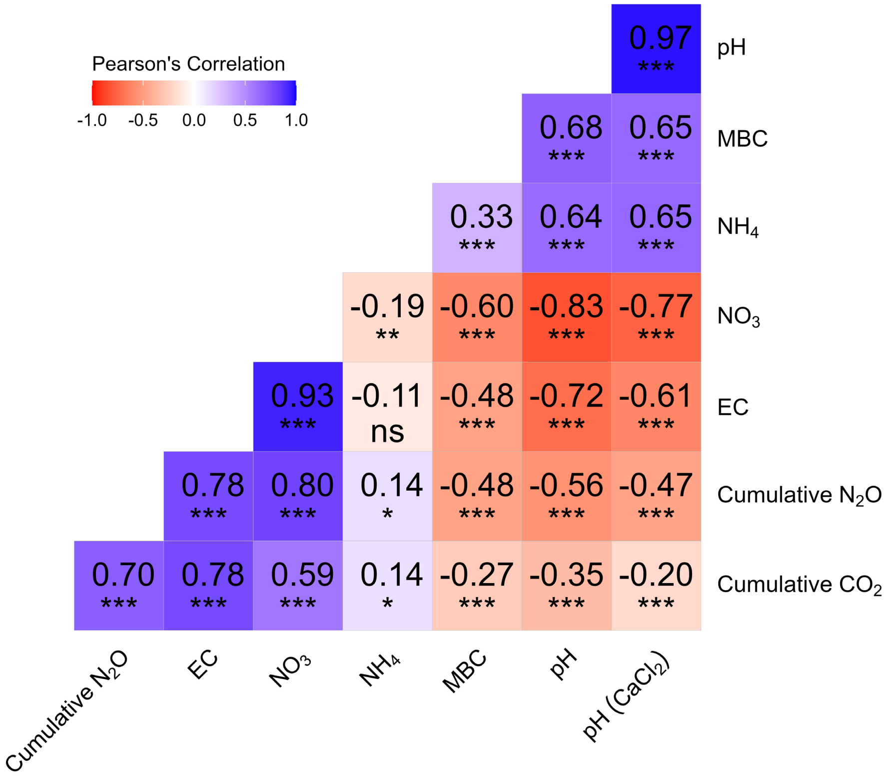
FIGURE 5 Microbial biomass carbon (MBC; µg C g soil^{-1}) evolution for nine treatments during 56 days of incubation. LD, Liquid digestate; SD, Solid digestate; UAN 50, Urea ammonium nitrate applied at 50 kg ha^{-1} total N; UAN 100, Urea ammonium nitrate applied at 100 ha^{-1} total N. Points represent experimental data. Table S9 shows standard errors.

higher level of MBC than the control (+32%; $p < .001$) (Figure 5; Table S9); it also had significantly higher MBC than all other treatments except SD. The MBC values in SD + UAN 50 increased from 28 to 56 days (Figure 5). Significant differences in MBC among treatments occurred at 0.5, 3, 14, 28 and 56 days. The lack of significant differences in MBC between treatments and the control are likely because of the high total C in the control soil (7.04%). Further studies are needed on the effect of different treatments on MBC in low-carbon soils. The increased C source and nitrogen can promote microbial biomass biosynthesis and accumulation (Alburquerque et al., 2012; Cattin et al., 2021). Therefore, higher levels of MBC in SD + UAN 50 than other amendments are likely because of the SD having increased total C (36.93% total C; Table 1), labile carbon and available nitrogen because of UAN application. The study by Odlare et al. (2008) found higher degradable carbon in digestate than in compost, which increased microbial activity. Also, Cattin et al. (2021) and Alburquerque et al. (2012) reported higher MBC levels in SD than the control because of high total N and C input. Cattin et al. (2021) concluded that SD contributed to a higher MBC than LD because of higher total carbon and lower total N, increasing C input rates.

3.4 | Pearson's correlation and principal component analysis (PCA)

Pearson's correlation coefficients in Figure 6 show that there is significant difference among all parameters during the incubation period. Cumulative N_2O emission was positively correlated with soil NO_3^-, EC and cumulative CO_2 (R^2 values of .80, .78 and .70, respectively), indicating that higher levels of microbial activity and nitrate should increase N_2O emissions because of microbial nitrification and denitrification processes (Shcherbak et al., 2014). Moreover, cumulative N_2O emissions negatively correlated with pH with a weak regression (R^2 value = −.56), consistent with the literature (Kunhikrishnan et al., 2016; Wang et al., 2018). Moreover, Wang et al. (2018) reported how pH is a chief modifier of N_2O emissions, particularly with N fertilization. Cumulative CO_2 emissions positively correlated with soil NO_3^- and EC.

NH_4^+ positively correlated with N_2O emission and pH with a weak to medium regression (R^2 values of .71 and .64, respectively). NO_3^- positively correlated with EC with a strong regression (R^2 value = .93). Moreover, NO_3^- negatively correlated with pH and MBC with a medium to strong regression (R^2 values of −.83 and −.60, respectively). As expected, NO_3^- ions had a strong positive correlation



	Cumulative N_2O	EC	NO_3	NH_4	MBC	pH	pH ($CaCl_2$)
pH							0.97 ***
MBC						0.68 ***	0.65 ***
NH_4					0.33 ***	0.64 ***	0.65 ***
NO_3				-0.19 **	-0.60 ***	-0.83 ***	-0.77 ***
EC			0.93 ***	-0.11 ns	-0.48 ***	-0.72 ***	-0.61 ***
Cumulative N_2O		0.78 ***	0.80 ***	0.14 *	-0.48 ***	-0.56 ***	-0.47 ***
Cumulative CO_2	0.70 ***	0.78 ***	0.59 ***	0.14 *	-0.27 ***	-0.35 ***	-0.20 ***

ns $p >= 0.05$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$

FIGURE 6 Pearson's correlation coefficients for eight parameters during 56 days of incubation.

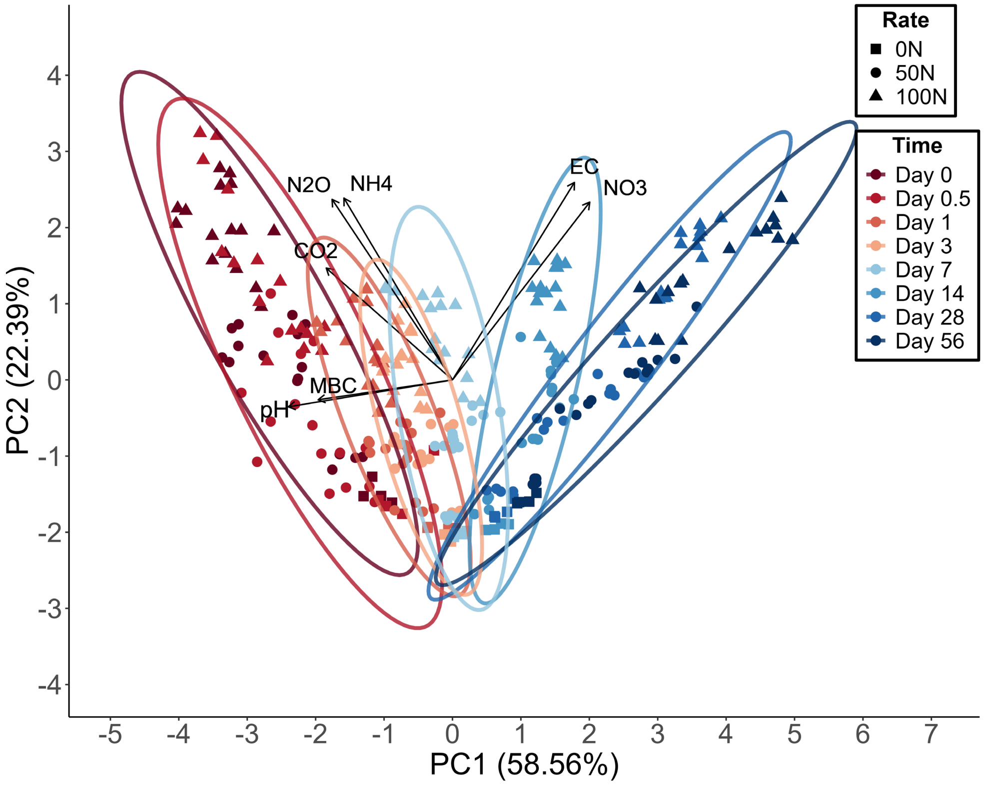


FIGURE 7 Principal component analysis for seven soil parameters over during 56 days of incubation.

with EC. Increased NH_4^+ levels are likely correlated with EC; however, as NH_4^+ nitrified during the incubation period and the analysis grouped the sum of the incubation time points, Pearson's correlation coefficient fails to show this relationship. The correlation graph in Figure S3 shows that the regression is not linear and hence is not accurate for Pearson's correlation.

The PCA in Figure 7 shows the evolution of variables over the incubation period. Day 0 to 7 had higher emissions of CO_2, N_2O, increased levels of NH_4^+, pH and MBC. After Day 7, NO_3^- and EC increased. The evolution from Day 0 to Day 56 shows how NH_4^+ mineralized into NO_3^-. As discussed in Section 3.1, pH decreased, and EC increased during the 56-day incubation because of NH_4^+ mineralization and the release of other ions. The PCA also shows that increasing the rate of N (100 N > 50 N > 0 N) increased gaseous emissions (CO_2, N_2O) and soil properties (NH_4^+, NO_3^- and EC).

4 | CONCLUSION

The study evaluated the effects of common and emerging food waste fertilizers (compost, LD and SD) on gaseous emissions, nitrogen dynamics and soil properties in a soil incubation study. LD reduced N_2O emissions by 23% compared with UAN despite having the same available N. SD and compost had reduced levels of available N compared with LD and UAN, reducing N_2O emissions. Thus, by adding food waste-derived soil amendments to soil, it can increase nitrogen retention, preventing losses from N_2O and potentially NH_3, which is commonly observed in conventional farming practices with the application of synthetic N fertilizers.

SD had the highest MBC and CO_2 emissions among the food waste fertilizers, indicating higher degradable carbon than LD and compost, and lower available nitrogen than LD. Compost did not release available N into the soil when applied. LD, SD and UAN decreased soil pH, and all treatments increased EC over the incubation period. Further research should include insights into the mechanisms of nitrogen retention in these amendments. Ammonia emission measurements should be included to provide a comprehensive understanding of nitrogen dynamics within the soil. Moreover, further investigations should focus on optimizing ammonium retention during the evaporation of LD to reduce storage and handling constraints in the anaerobic digestion process.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

DECLARATION

During the preparation of this work, the authors used ChatGPT-GPT4 (OpenAI) in order to generate code and increase readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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